EVER UPWARDS

ISRO

IN IMAGES

P V MANORANJAN RAO
B N SURESH
V P BALAGANGADHARAN

इसरो ISRO

Universities Press

SHOUT
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IT

EVER UPWARDS

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इसरो isro

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Panoramic view of ISRO Propulsion Complex, Mahendragiri

In memory of
Vikram A Sarabhai

Ever Upwards: Isro in Images

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Ever Upwards

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Foreword

I am extremely delighted to write the foreword for the coffee table book *Ever Upwards: ISRO in images*. In chronicling success stories, it is important to connect various milestone events with the people behind them and their thought process. This book beautifully captures the ISRO story and the people behind it through a series of visually stunning images.

Dr Vikram Sarabhai was a visionary leader who foresaw the role of space science and technology in the development of India and played a crucial role in convincing the Government to initiate Space Research Programmes in India. If Dr Vikram Sarabhai sowed the seeds of Space Research in India, Prof. Satish Dhawan laid down the organizational framework for ISRO, which has been responsible for the continued success of the Indian Space Programme.

I have had a very long association with the authors, Dr PV Manoranjan Rao, Dr BN Suresh and Sri VP Balagangadharan, during my career in ISRO and they have been working on this book for the last five years. I am glad that the book is slated for release in August 2019, which marks the birth centenary of the father of the Indian Space Programme – Dr Vikram A Sarabhai.

Some of the pictures are an absolute treat for the eyes. After all, Space Technology is known for its spectacle of awesome visuals, including thrilling rocket lift-offs that shake the earth for miles. Enjoy the show!

I recommend this book to all my compatriots on whose support ISRO thrives.

I once again thank the authors for all the trouble they have taken in creating this book of images. I wish the book all success. It deserves pan-Indian readership.

K Sivan

18 June 2019 *Chairman, ISRO*

Introduction

In our earlier compendium, *From Fishing Hamlet to Red Planet,* published by Harper Collins and released in 2015, we had promised our readers that we would be bringing out a visual complement to the compendium. This coffee table book is the result. We had sourced thousands of photographs, from which we have selected the ones that appear in this book.

Chapter 1, titled 'The Sarabhai Decade' is all about the man who launched the Indian space programme in the early 1960s. It has about 50 photographs, some of which have never been seen by the current generation of people either inside or outside ISRO. These pictures speak for themselves. Looking at them, one finds it hard to believe that Sarabhai left us half a century ago. Many of the pioneers in these pictures are no longer with us, but their images remind us of their seminal contributions to our space programme.

When Vikram Sarabhai suddenly died in his sleep, at the peak of his creative best, he was 52. In an inspired move, Prime Minister Indira Gandhi chose Satish Dhawan, Director of the Indian Institute of Science, Bangalore, to succeed Sarabhai. (Before Dhawan took over, for a brief period, MGK Menon was the Chairman of ISRO). When Dhawan took charge of the space programme, he too was 52. This coincidence in age seems, in retrospect, strangely appropriate because Dhawan started where Sarabhai had left-off. While Sarabhai was a visionary scientist-cum-institution builder, Dhawan was a practical engineer who provided flesh and blood to the dreams of Sarabhai. It was Dhawan who created the Department of Space (DOS) and brought ISRO under its fold. More importantly, he provided the organisational structure to our space programme, which still drives ISRO today. Dhawan transformed the fledgling ISRO of Sarabhai into a technological giant of our country. He made ISRO/DOS an exemplar of excellence in a Government set-up. Politicians may fight fiercely with each other over their differing ideologies,

but they are all united in supporting ISRO. For all this, we must be grateful to Dhawan. Chapter 2, titled 'The Dhawan Era' is all about the man known as the Gentle Colossus.

If there is one area in which technologically advanced countries are averse to collaborating with others, it is launch vehicles; that is, rockets capable of orbiting satellites. This is because these rockets have dual use: civilian and military. Chapter 3 is about the rockets of ISRO. By successfully launching SLV-3 in 1980, ISRO broke the monopoly of a five-member elite club of nations guarding this technology! The Project Director of SLV-3, APJ Abdul Kalam, later became the President of India, a rare distinction for a technologist. The success of SLV-3 was followed by two successive failures of the ASLV, plunging ISRO into gloom. But the lessons learned from these failures laid the foundation for ISRO's operational launch vehicles, starting from the Polar Satellite Launch Vehicle (PSLV), Geosynchronous Satellite Launch Vehicle (GSLV) and now, GSLV Mk III, which is ISRO's most powerful rocket. GSLV Mk III is also the vehicle that is expected to take people into space (Gaganyaan). Nothing in space technology can come close to the spectacle of a powerful rocket shooting up, defying gravity. This chapter has some of those arresting images.

The main purpose in developing launch vehicles is, of course, to orbit satellites or to send probes to heavenly bodies such as the Moon, Mars, etc. Both Sarabhai and Dhawan chose UR Rao to lead ISRO's satellite programme. Starting with the scientific satellite, *Aryabhata,* in 1975, this programme quickly progressed to the operational phase with the Indian Remote Sensing Satellite (IRS-1A) launched by the Soviet Union (now Russia) in 1988. Today, ISRO has four types of operational satellites in orbit: remote sensing, communication, scientific and navigation; the constellation comprises over 40 satellites. Instead of describing all these satellites, we deal in Chapter 4 only with those of historical importance that paved the way for the current constellation. We have also included in this chapter a few pictures related to the recovery of an orbiting satellite carried out under the programme known as SRE-1 (Satellite Capsule Recovery Experiment-1).

One of the very first things Satish Dhawan emphasised when he took over as Chairman of ISRO was the role of Indian industry in our space programme. He had realised quite early on that without robust industrial participation, the space programme could not be sustained for long. In the 1970s, he sent a team headed by Kalam in search of industrial partners. This exercise resulted in ISRO identifying over 50 industries as partners. In the following decades, ISRO pursued this industrial policy vigorously. Today, a substantial part of ISRO's budget goes to industry. This industry participation in the national space programme is all set to grow further.

Chapter 5 is about ISRO–Industry collaboration. It is to be noted that this collaboration is a two-way street; while ISRO gains by freeing substantial human resources from routine jobs, the industry gains by absorbing strict quality control protocols, including detailed documentation, certification, etc. The industry gets to work on cutting edge technology.

When Sarabhai launched the space programme, he had clearly stated only one objective: to harness space for national development. He had even visualised applications for which no proven technology existed at that time. Even today, that is, 50 years after the creation of ISRO, emphasis on applications is visible. Recently, when GSAT-31 was launched on 6 February 2019, K Sivan, Chairman of ISRO, said: "Although GSAT-31 is not a heavy satellite, we are using the services of Arianespace, as it is an emergency launch to replace a dying INSAT satellite so that communication services are not affected." Chapter 6 deals with applications. Quite literally, the number of ways space technology can be harnessed is limited only by our imagination! In this chapter, we touch upon the following applications: telecommunications including TV, satellite news gathering, VSAT network, mobile satellite service, tele-education, telemedicine, etc. Other applications are related to meteorology, including cyclone detection and monitoring, disaster monitoring and management, agriculture, forest inventory, water resources and conservation of heritage sites. We have only listed these applications with photographs without any technical explanation of how it is done. This is because our target readership is the general reader.

We have given the title 'Of People and Places' to Chapter 7. Our intention in designing this chapter is to convey the idea that people are the most

valuable asset of our space programme, along with the sophisticated infrastructure ISRO has built across the country. Though we have tried to be eclectic in our choice of pictures, we are painfully aware that we could not do full justice to the idea of "people". All said, we had to restrict the number of photographs to prevent the physical size of this volume from becoming too unwieldy.

We end this volume with 'Future: A Glimpse'. If what ISRO has achieved so far is any indication, the future looks very bright and exciting. In a few pages, we cover what ISRO intends to do in the next two decades!

Finally, we hope the reader will take in his or her stride our failings in creating this coffee table book.

PV Manoranjan Rao, BN Suresh, VP Balagangadharan

Acknowledgments

This coffee table book is the result of the cooperation extended to us by all the Centres and Units of ISRO, including the ISRO Headquarters in Bengaluru. Several individuals of the ISRO fraternity, both serving and retired, have helped us curate this book. Unfortunately, we cannot name them all because of the constraints imposed on us by the size of this volume.

We have freely used material from earlier ISRO publications. Special mention must be made of "images india", an excellent compilation of satellite images published by the National Remote Sensing Centre (NRSC) in 2006. We have reproduced some of those images.

We are grateful to Dr K Sivan, Chairman of ISRO, for his Foreword and for his constant support that is responsible for the publication of this book.

PV Manoranjan Rao

BN Suresh

VP Balagangadharan

Contents

Foreword

Introduction

Acknowledgments

The Sarabhai Decade

The Dhawan Era

Rockets of ISRO

Satellites of ISRO

ISRO and Industry

ISRO in the Service of the Nation

Of People and Places

Future: A Glimpse

List of Abbreviations

Vikram A Sarabhai

The Sarabhai Decade

Introduction

Commenting on the gumption of Vikram Sarabhai in launching the nation's space programme in 1963 with no infrastructure and with only a handful of scientists and engineers with no exposure to space technology, EV Chitnis, a veteran of ISRO, said: "When you want to do something entirely new you should not start with writing a project report that would soon become very limiting… We don't know at the start what we will be able to do. And then the project develops and things develop and objectives develop as you go. You don't start with objectives to fulfil; you start and then create new objectives which are in the spirit of what you wanted to do. This is a wonderful thing. Such things don't happen nowadays!". This quote captures the spirit of how Sarabhai did what he did.

A building in Retreat, the sprawling residential complex of the Sarabhais in Ahmedabad. It was here that Vikram Sarabhai had his own laboratory, which was to become the seed for the Physical Research Laboratory (PRL) campus in Navrangpura, Ahmedabad. Courtesy: PRL, Ahmedabad.

The foundation stone for PRL was laid by CV Raman on 15 February 1952. Speaking at the function was SS Bhatnagar, the first Director General of the Council of Scientific & Industrial Research (CSIR) and also the first Chairman of the University Grants Commission. Seated second from left is Homi Bhabha and fourth from left, CV Raman. Courtesy: PRL, Ahmedabad.

Two allies

Sarabhai had two powerful allies in his mission of bringing the fruits of space technology to India: Jawaharlal Nehru, the first Prime Minister of independent India, and Homi Bhabha, the czar of organised research in India in those days. All three of them shared a common creed: that modern science and technology are indispensable to the development of the country. Nehru declared: “Science alone can solve the problems of hunger and poverty, insanitation and illiteracy, of superstition and deadening custom and tradition, of vast resources running to waste, of a rich country inhabited by starving people.”

In 1958, that is, within a year of the launch of Sputnik-1, Nehru passed a scientific policy resolution in parliament which committed his government to, “offering good conditions of service to scientists and according them an honoured position, by associating scientists with the formulation of policies… .”

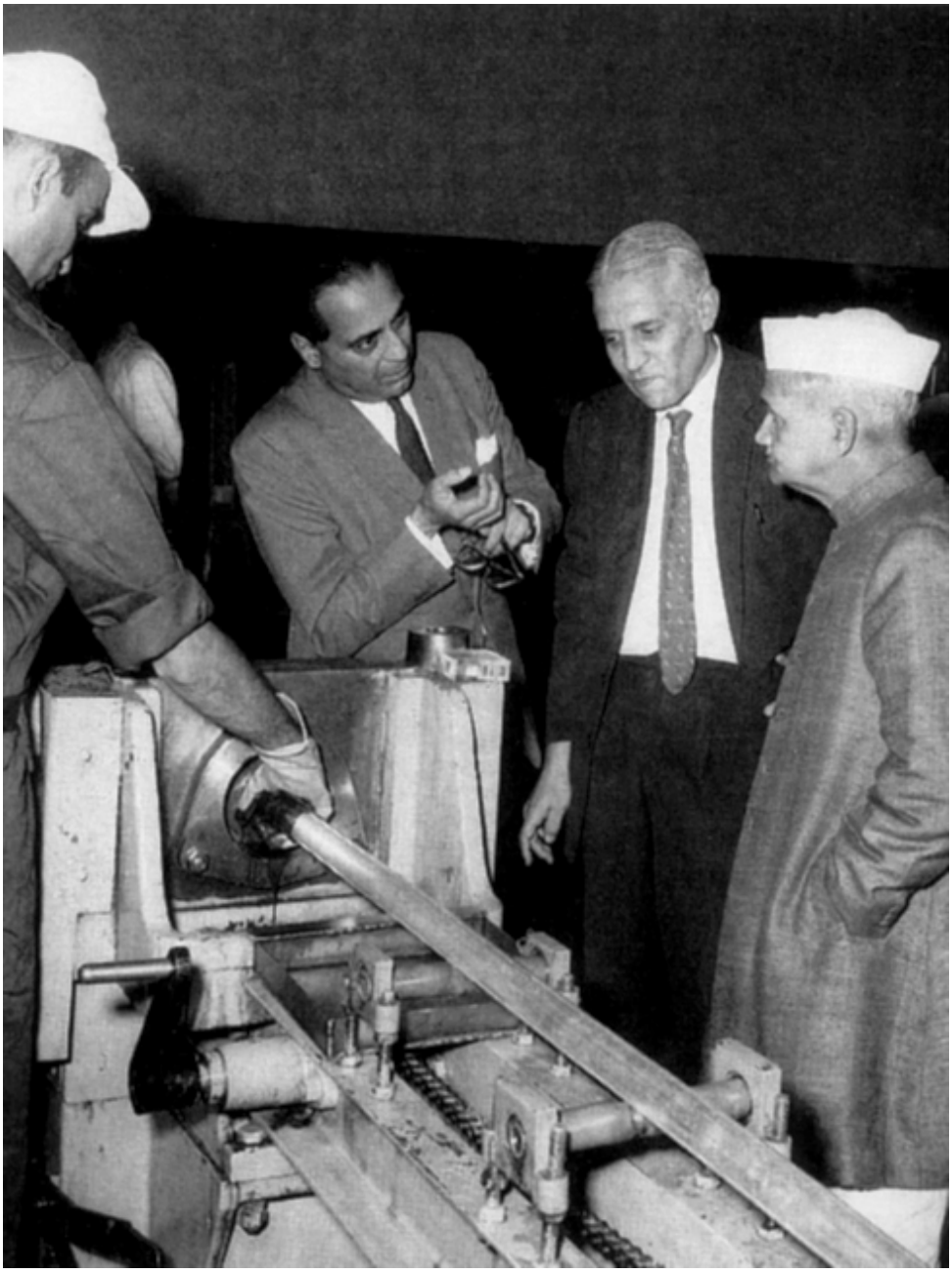
In August 1961, Nehru's government entrusted the responsibility of looking after space research and peaceful uses of outer space to the Department of Atomic Energy (DAE), whose Secretary was Bhabha. The very neat year, Bhabha constituted the Indian National Committee for Space Research (INCOSPAR), with Sarabhai as its Chairman. And, as they say, the rest is history. (INCOSPAR is the national counterpart of the global COSPAR, formed in the wake of Sputnik-l).

The first building on the campus of PRL was opened by Prime Minister Jawaharlal Nehru on 10 April 1954. PRL is generally recognised as the cradle of the Indian space programme. Picture shows Nehru with Sarabhai in PRL. Courtesy: PRL, Ahmedabad.

Homi Bhabha (glass in one hand and the other on the table) showing Prime Minister Nehru (extreme left) the model of the Tata Institute of Fundamental Research (TIFR). TO Nehru's left is SS Bhatnagar. To Bhabha's left is Morarji Desai, who later became the Prime Minister of India in 1977.

Between Bhabha and Desai, in the background, is MC Chagla, the eminent jurist and diplomat. Courtesy: TIFR Archives.

Homi Bhabha (right) and Vikram Sarabhai in discussion at a conference in Jaipur, December 1963. Bhabha, senior in age by about 10 years, was a mentor to Sarabhai. While Bhabha built his international reputation as a theoretical physicist, Sarabhai was an experimental researcher. Both worked in cosmic rays; both came from rich and cultured families. Bhabha brought nuclear technology to India and Sarabhai, space technology. Courtesy: TIFR Archives.



Lal Bahadur Shastri (extreme right), who succeeded Nehru as Prime Minister in 1964, visiting the Atomic Energy Establishment, Trombay. Shastri suddenly died under mysterious circumstances on the very day (10 January 1966) he signed a peace treaty with Pakistan at Tashkent, USSR. The mystery remains unsolved. In 1972, Brahm Prakash (second from right) became the first Director of the Vikram Sarabhai Space Centre at Trivandrum (now Thiruvananthapuram). To the right of Brahm Prakash is Bhabha.

Thumba Equatorial Rocket Launching Station (TERLS)

For untold centuries, Thumba near Trivandrum (now Thiruvananthapuram) had been an obscure fishing village, on the west coast of India. Little did the fisherfolk realise that their sleepy village 'possessed' a unique geophysical treasure. Thumba lay close to the magnetic equator – a happenstance that Sarabhai was quick to exploit. There are some geophysical phenomena unique to the magnetic equator. One of them is the equatorial electrojet, an electric current system at heights of around 110 km directly over the magnetic equator.

It would be convenient, Sarabhai argued, for the world's scientific community to explore the electrojet and its associated processes if a sounding rocket range could be established in Thumba. Earlier, COSPAR too had urged the international community to establish sounding rocket stations close to the magnetic equator. On 21 November 1963, a sounding rocket took off from the shores of Thumba, ending its anonymity. Thus was born the Thumba Equatorial Rocket Launching Station (TERLS).

The birth of TERLS was the result of international cooperation. The sounding rocket (Nike-Apache) and some tracking equipment came from the USA while the sodium vapour payload came from France. The Soviet Union chipped in with the MINSK computer, a vibration table, a helicopter and a boat. TERLS was a tribute to the charisma of Sarabhai, who could persuade the bitter enemies of the Cold War to come together in the service of science.

In 1968, TERLS was dedicated to the United Nations by Prime Minister Indira Gandhi. Sarabhai was resolutely clear about why India should pursue space: "…we must be second to none in the application of advanced technologies to the real problems of man and society which we find in our country." He also emphasised that the progress achieved through the application of space technology must be "measured in hard economic and social terms."

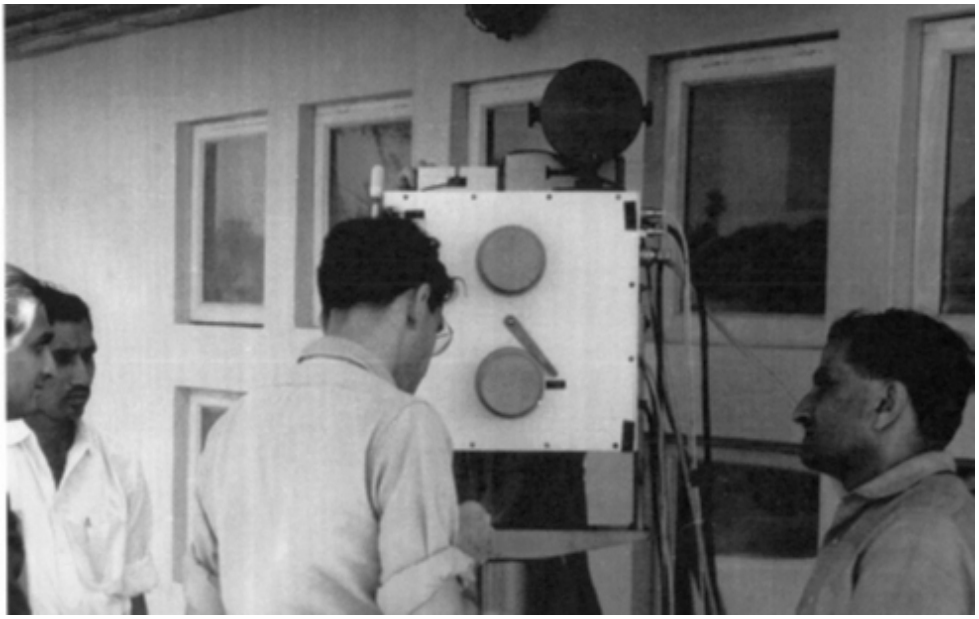
In 1963 When the Indian space programme was launched at Thumba, it was an obscure fishing village near Trivandrum. On 21 November 1963, the first rocket took off from Thumba, announcing the birth of the Thumba Equatorial Rocket Launching station (TERLS). Fishermen at work in those days.

St. Mary Magdalene Church

The Indian space programme has the unique distinction of being born in a place of worship: the St. Mary Magdalene Church. When, in 1962, the Department of Atomic Energy (DAE) acquired land of about "one square mile" of coastal area in Thumba near Trivandrum, there was a church in the middle. This acquisition was for establishing the Thumba Equatorial Rocket Launching Station (TERLS). The only decent and reasonably big building in the whole area was this church. ISRO, which came into existence in 1969, owes a permanent debt to the Rt Rev. Dr Peter Bernard Pereira, the Bishop of Trivandrum. It was Bishop Pereira who persuaded his flock to give up the church in the greater interests of the country. K Madhavan Nair, District Collector of Trivandrum, was responsible for the speedy acquisition of land.

The evacuated people, mostly fisherfolk, were resettled in a nearby place called Pallithura, where a new church was built by the DAE.

Today, the St. Mary Magdalene Church houses a space museum which is visited by thousands every year.



Jacques Blamont from France (facing the camera, above) personally brought the sodium vapour payload for the first rocket flight from Thumba on 21 November 1963. Over the years, the personal bond between Blamont and Sarabhai (seen on the right of Blamont in both pictures) grew stronger, resulting in close cooperation between France and India in space technology. For his pioneering role in the early years of the national space programme, the Government of India honoured him with the Padma Shri in 2015. Courtesy: Jacques Blamont.

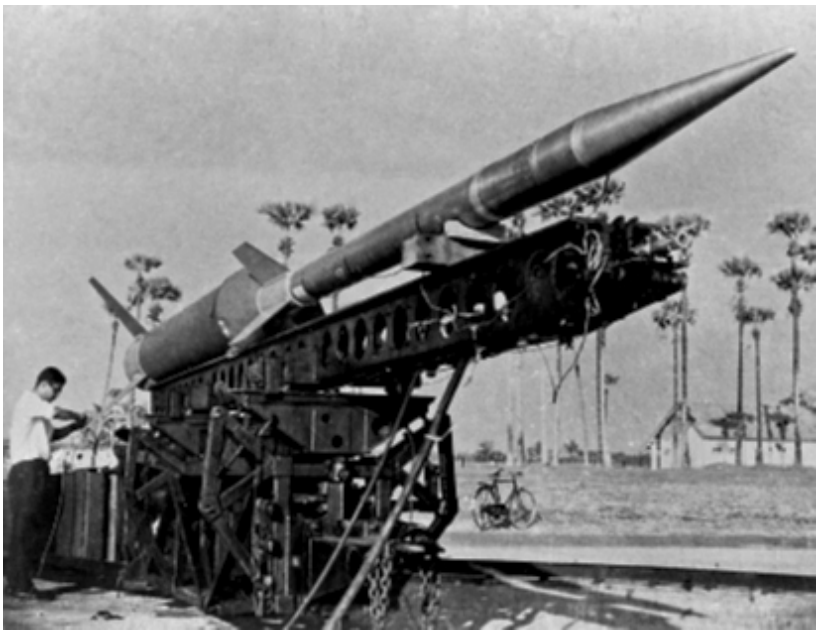
Looking at the stars

The situation in India when Sarabhai launched his space initiative in the early 1960s was bleak:

- No one had any experience in any branch of space technology.
- The only infrastructure available in Thumba was an old church, known as St. Mary Magdalene Church.
- No institutional framework for space research had been created.
- People and policy makers were yet to be convinced of the benefits of space technology.
- The general mood of the people was one of despair caused partly by the humiliating border clash with a neighbour in the north and large-scale dependence on import of food.

The National Aeronautics and Space Administration (NASA) of the USA played a vital role in launching the Indian space programme at Thumba. Some of the early recruits of Sarabhai were trained by NASA at its Wallops station in Virginia. In the picture, they are familiarising themselves with the operation of the Kodak K-24 aerial camera suitably modified for vapour trail photography with custom-made mountings. They could be operated remotely. These cameras were used to photograph the sodium vapour clouds released by the rockets launched from Thumba. The purpose of such experiments was to measure winds in the upper atmosphere. From left: B Ramakrishna Rao, AS Prakasa Rao, Pramod Kale (partially seen), R Aravamudan and HGS Murthy. Courtesy: R Aravamudan.

From left: R Aravamudan, APJ Abdul Kalam, HGS Murthy, B Ramakrishna Rao and D Easwaradas.



NASA also supplied Nike-Apache sounding rockets (including the one for the inaugural flight) and some tracking equipment. Nike is the name of the booster (or the first stage) while Apache is the name of the second stage. The picture shows an assembled Nike-Apache at Thumba. Note the bicycle in the background; it was the only readily available mode of transport in TERLS in the 1960s.

The situation could be best described by what Oscar Wilde once wrote: “We are all in the gutter but some of us are looking at the stars.”

Yes, Nehru, Bhabha and Sarabhai were looking at the stars so that after over five decades, ISRO could reach literally for the stars through the now famous Mars Orbiter Mission (also known as Mangalyaan).

Sarabhai, with a band of greenhorns waiting to do his bidding, moved fast. He consulted whomsoever he could, sent his engineers wherever he could for training, for attending conferences or just to meet experts in the field. Thus, during 1965–67, Hideo Itokawa, the space pioneer of Japan, was a constant companion of Sarabhai. In 1962, even before TERLS formally came into existence, Sarabhai had sent a small band of newly recruited engineers to NASA for training that included Kalam.

In spite of the poor quality of the photograph, we have included it for its archival value. This was taken hours before the launch of the first rocket from Thumba on 21 November 1963. From right: HGS Murthy, Homi Bhabha and Vikram Sarabhai. This is the only picture we know of that shows Sarabhai and Bhabha together in Thumba on 21 November 1963. Courtesy: Malayala Manorama dated 23 November 1963.

In 1964, the Tokyo Olympic Games were transmitted live across the Pacific by the American satellite, Syncom 3. Nothing could be more convincing than this demonstration of the power of satellite communication. Sarabhai hurriedly assembled a team of engineers to set up what is known as the

Experimental Satellite Communication Earth Station (ESCES) in Ahmedabad. This was done with assistance from UNDP (United Nations Development Programme) and ITU (International Telecommunication Union). The 14-meter dish antenna was set up with equipment from NEC, Japan. ESCES became operational in 1967 and was used to train over 200 engineers, both from India and from other developing countries, in satellite and other associated technologies.

In the same year, an arrangement was concluded with a French firm to manufacture, under licence, a two-stage sounding rocket called Centaur. Over a period, this arrangement lead to the creation of the Rocket Propellant Plant (RPP) and Rocket Fabrication Facility (RFF) in Thumba.

In 1965, Sarabhai set up the Space Science and Technology Centre (SSTC) near Thumba, on what is called Veli Hills, which commands a beautiful view of the Arabian Sea. (He had an inner urge to be surrounded by scenic beauty). The mandate for SSTC was to conduct R&D on rocket systems and components. The most important task for SSTC, made explicit by Sarabhai, was to develop indigenous satellite launch capability.

Thus were sown the seeds for the future PSLVs and GSLVs of ISRO, described in Chapter 3.

Displaying full trust in people working under him, Sarabhai gave them complete freedom to do what they wanted to do in their domain. The result was: several groups were working on sounding rocket designs; at least two groups were working on the development of solid propellants; others on fibre-reinforced plastics, pyro-systems and so on. For example, there was a surfeit of at least 15 different types of sounding rocket designs on which people were working. From this ‘technological melting pot’ grew a set of professionals who are now considered veterans of ISRO. In time, they delivered the goods, redeeming the faith that Sarabhai had reposed in them.

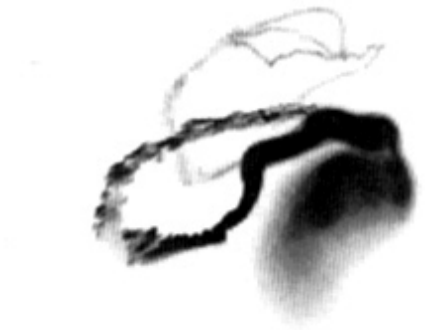
Legacy of Sarabhai

Sarabhai created ISRO on 15 August 1969, which marked the 22nd anniversary of India’s independence. He flagged off the development of India’s first satellite launch vehicle; completed all the formalities for an

agreement with the Soviet Union for the launch of India's first satellite (Aryabhata); started building a launch complex on the east coast of India (Sriharikota); saw the launch of India's first sounding rocket (a tiny thing that weighed less than 7 kg); took over the reins of the Atomic Energy Commission following the death of Bhabha in a plane crash; signed an MOU with NASA for the conduct of a joint instructional television experiment using NASA's ATS-F satellite (later known as ATS-6); drew the road map for ISRO to be followed during the decade 1970–80 and then died in his sleep on 30 December 1971. He was just 52. He bequeathed the space programme to the nation.

★★★

Nike-Apache on the launch pad.



The blob of sodium vapour released by the rocket in the upper atmosphere. By photographing this cloud from three different places, one could measure winds at those heights.

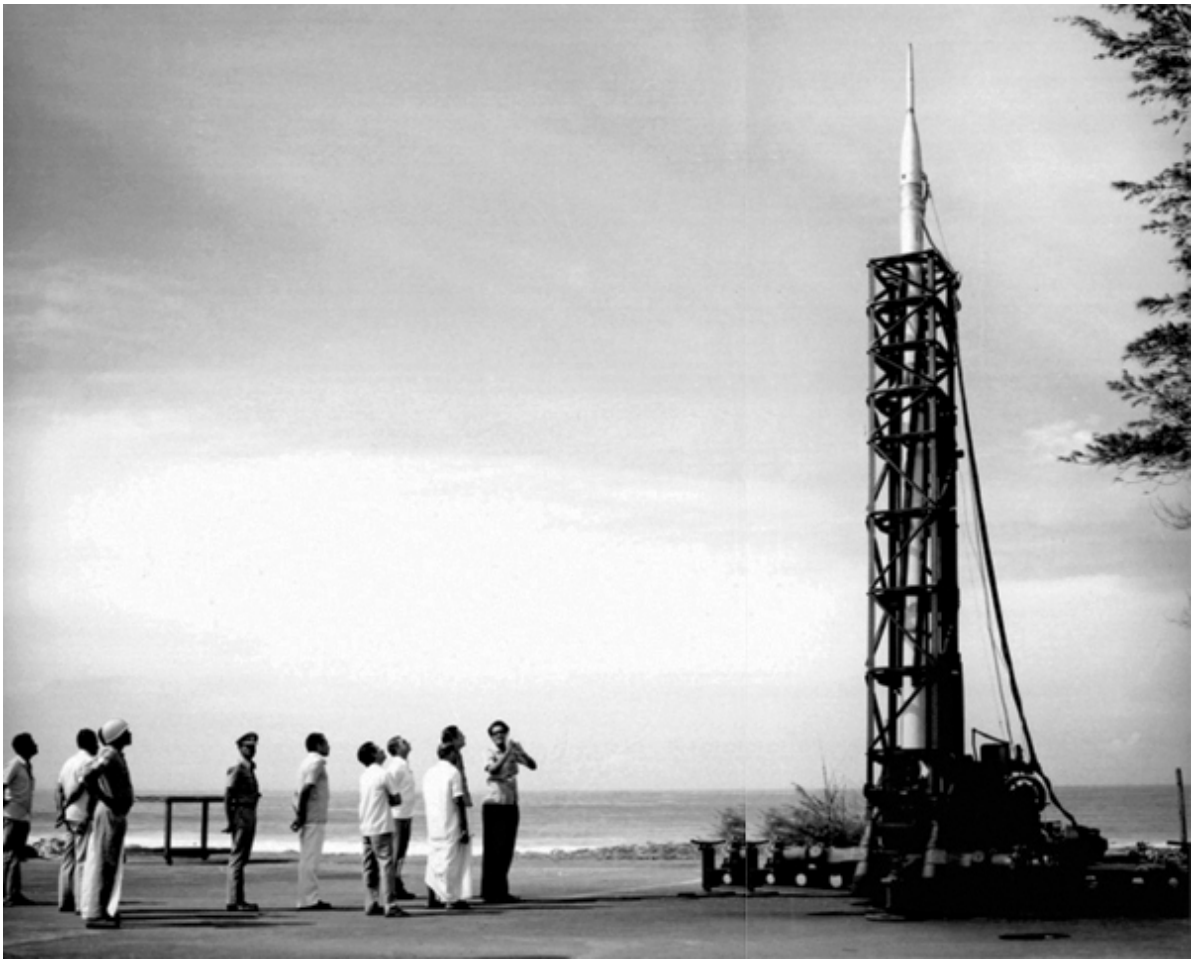
The very first rocket flight from Thumba was watched by boy scouts, among others.

PD Bhavsar (right), the Project Director for the first sodium vapour cloud experiment, watching for the release of the sodium vapour. His colleagues in the picture could not be identified.

The Centaur sounding rocket from France on the launcher. This rocket was later produced in India under license from the French firm, Sud Aviation.

Informal discussions were common in TERLS in the 1960s, From left: EV Chitnis, R Aravamudan, D Easwaradas, (only head seen, not identified), SC Gupta, VR *Gowariker (partly seen), Sarabhai (leaning on the wall) and PD Bhavasar.*

Skua, the British sounding rocket, was launched using a long tube.



The sounding rocket from the Soviet Union (now Russia), known as M-100, ruled the skies over Thumba for over two decades (1970–1993). During this period, without fail, every Wednesday evening the M-100 would take off from TERLS. It was a two-stage rocket weighing 480 kg at lift-off. It could reach a payload of 70 kg to an altitude of about 85 km. Because of its reliability, it had become the darling of meteorologists and aeronomers, who study the physics and chemistry of the upper atmosphere. Well over 1100 of these rockets were launched from TERLS. Picture shows R Aravamudan (closest to the rocket) describing to the visitors the working of the M-100, which is seen on its spiral launcher.

YJ Rao (with spectacles) is showing Sarabhai the RH-75.

The very first indigenous rocket made by ISRO was known as RH-75 (RH stands for Rohini and 75 refers to the diameter of the rocket in mm). It was made from readily available extruded aluminium alloy tubes from the market! Even the propellant block was made from a readily available cordite block from a factory in Aravancadu (now Aruvankadu) in Tamil Nadu. The first RH-75 with indigenous composite propellant was launched on 21 February 1969. It was given a high sounding name: Dynamic Test Vehicle. Weighing some 7 kg, it reached an altitude of 6 km. No doubt, RH-75 was a glorified Deepavali rocket but it was The Beginning of indigenous rocketry in ISRO! The origins of the Polar Satellite Launch Vehicles (PSLV) and Geosynchronous Satellite Launch Vehicles (GSLV) of ISRO can be traced to this humble RH-75!
Pictures show some early scenes.

VJ Varkey pouring a resin into the shell of RH-75 for end-inhibition. Later, the slurry would solidify.

RH-75 in flight.

Vikram Sarabhai, the newly appointed Chairman of the Atomic Energy Commission, addressing employees of the Atomic Energy Establishment, gathered to condole the death of Homi Bhabha, who was killed in an air crash on Mont Blanc on 24 January 1966. Courtesy: TIFR Archives.

Vikram Sarabhai addressing the gathering. Sitting extreme left: JRD Tata, the iconic industrialist of India, and extreme right: EMS Namboodiripad, India's first democratically elected communist Chief Minister (of Kerala). On his right, Indira Gandhi, and on her right, the Governor of Kerala, V Viswanathan.

2 February 1968 was a memorable day in the evolution of the Indian space programme. On that day, Prime Minister Indira Gandhi dedicated TERLS to the United Nations, thus ensuring global recognition to the Range. She unveiled a bronze plaque commemorating this dedication. The function was attended by a large number of dignitaries from India and abroad, as the photograph above and those on the next two pages show. Expressing India's gratitude to the UN and the countries helping its space programme, the Prime Minister described TERLS as a "symbol of international cooperation and India's onward and upward progress."
Three rockets were launched to mark the occasion: India's RH-75 at 2:45 p.m., NASA's Nike-Apache at 6:55 p.m. and France's Centaur at 7:15 p.m.

Dedication of TERLS to the United Nations: 2 February 1968

The Prime Minister addressing the gathering.

Indira Gandhi and Sarabhai with some of the foreign dignitaries.

Indira Gandhi pressing the button to launch the rocket. Seen are: HGS Murthy, Director of TERLS (with spectacles), Sarabhai and PD Bhavsar (with tie).

Dedication of TERLS to the United Nations: 2 February 1968

On the same day, the housing colony built for the fishermen displaced by TERLS was inaugurated. Standing at extreme right on the dais was Bishop Pereira, who was instrumental in handing over the St. Mary Magdalene Church to the DAE.

Seen at tea from right: Mrs. Gandhi, Sarabhai and Satish Dhawan, the Director of the Indian Institute of Science, Bangalore. Later, Dhawan became the Chairman of ISRO. He also created the Department of Space (DOS), becoming its Secretary.

This photograph of the rocket nose cone on a bicycle taken by Henri Cartier-Bresson soon went viral in the media. On the right: engineer, CR Sathya. His

assistant, Velappan Nair, is taking care of the nose cone. Courtesy: CR Sathya.

Sarabhai with the Chief Minister of Kerala, Achutha Menon (spectacled, facing the camera). On the right, HGS Murthy, Director of TERLS.

Sarabhai (left) with PR Pisharoty (middle), the grand old man of Indian meteorology, and Ms. Anna Mani, another meteorologist of the era.

Sarabhai with MR Kurup at a static test stand.

RATO (Rocket Assisted Take Off) motor at the test stand at TERLS. Picture shows (from left) JV Nair, MR Kurup, Thomas, M K Abdul Majeed, APJ Abdul Kalam and Gr. Cap. Narayanan.

AS Prakasa Rao (standing) and Pramod Kale during their training at NASA facilities in the 1960s.

Hideo Itokawa of Japan. He was popularly known as Dr Rocket in Japan. Itokawa helped Sarabhai in recruiting engineers for the fledgling space programme. He was also rumoured to have influenced some of the technical decisions made by Sarabhai.

Every visit of Sarabhai to TERLS brought all the prominent engineers together. Most of them would submit new proposals to Sarabhai for his approval. From left: YJ Rao, R Aravamudan, Sankaranarayanan, D Easwaradas, AE Muthunayagam, SC Gupta, Sarabhai, VR Gowariker and SR Thakore (who was Sarabhai's right-hand man at the Physical Research Laboratory, Ahmedabad).

Sarabhai set up the Space Science and Technology Centre (SSTC) on the Veli Hills near TERLS in 1965 as the main hub for R&D in rocketry. This building was known as the Main Building. This photograph was taken just after its completion and the scaffolding and other debris were yet to be cleared. It was later extended, but is still called the Main Building.

Vikram Sarabhai and Prime Minister Indira Gandhi in an unusually happy mood during the latter's visit to the Experimental Satellite Communication Earth Station (ESCES) in Ahmedabad. Left of Sarabhai and partially seen is Wg Cdr Rao, who was the Director of ESCES. The man with spectacles could not be identified.

At ESCES, from left: Indira Gandhi, Wg Cdr Rao (in formal suit), Hitendra Desai (who later became Chief Minister of Gujarat), Sarabhai, Col N Pant (spectacled), Cmdr Kohli, (not identified) and N Mohanty (extreme right).

Vikram Sarabhai explaining some details to Sonia Gandhi at ESCES.

Indira Gandhi and others photographed with the 14-metre-diameter dish antenna of ESCES in the background.

A Yanadi woman with a child.

"About 3000 people, including 600 Yanadi tribals, who work as labourers, reside on Sriharikota island. For safety reasons and to provide better amenities, the scattered population has been resettled in four colonies. All

the colonies are provided with approach roads, street lighting and drinking water. SHAR hospital runs a mobile clinic to these colonies at regular intervals. Immunisation, Family Welfare Programmes and Child Welfare Centre have been organised with the cooperation of the Andhra Pradesh Government. The inhabitants are given free general medicines and vitamins. The Andhra Pradesh Government is running two schools for the benefit of the children of the residents. In 1978, a community building was constructed in one colony. Other amenities include TV sets and children's play equipment." Quote from the Annual Report for the year 1978–79 of the Department of Space, Government of India.

Today, SHAR (Sriharikota Range) is where the main launch range of ISRO is located. It was renamed as Satish Dhawan Space Centre-SHAR on 5 September 2002 by Prime Minister Atal Bihari Vajpayee, who unveiled the name plaque through satellite link from his official residence in New Delhi.

A Yanadi woman with a child in front of their hut.

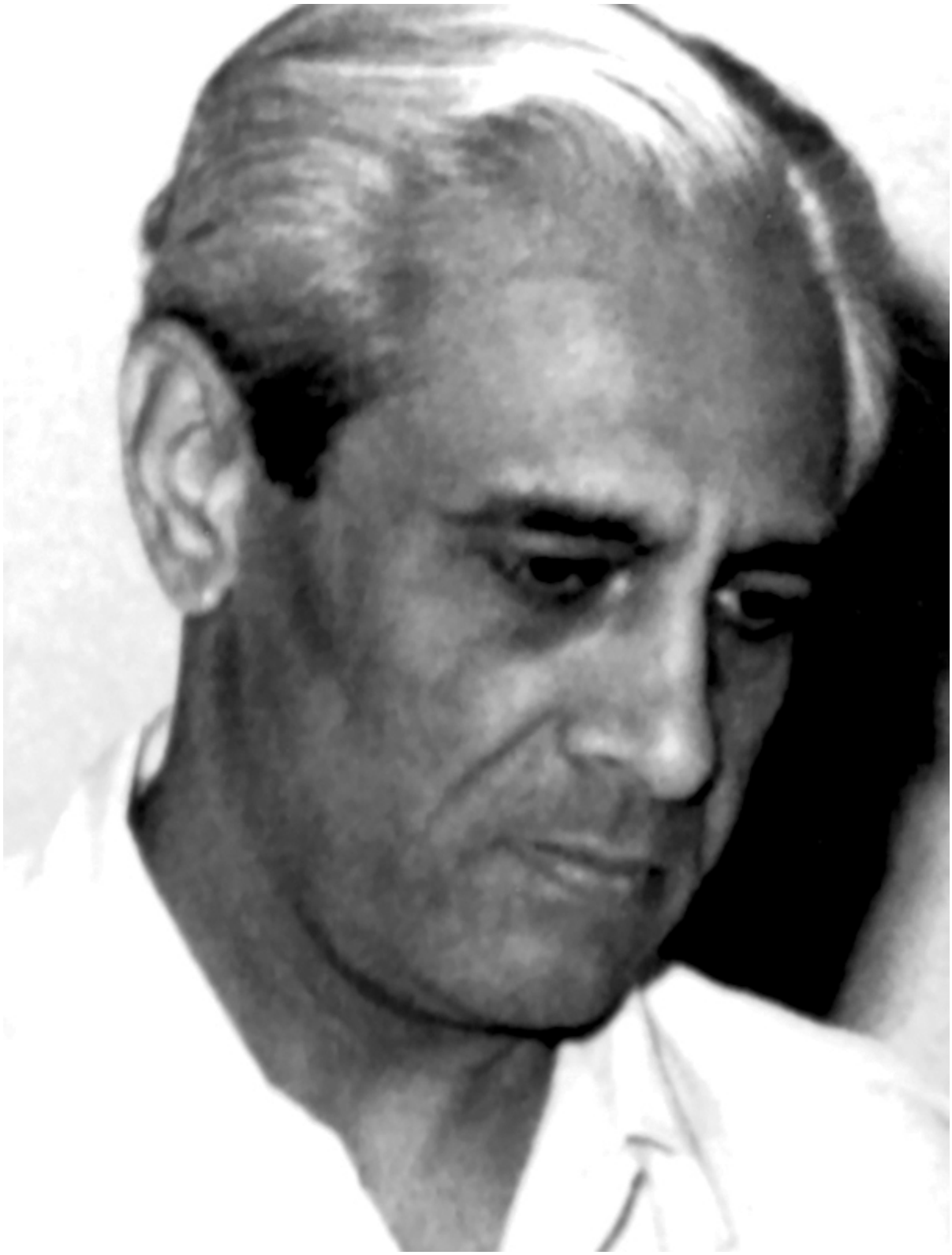
Photographs taken during Sarabhai's first visit to Sriharikota Range (SHAR) on 26 May 1969. From left: SC Gupta, HGS Murthy (back to camera), YJ Rao, (not identified), Sarabhai, RD John (only head seen, behind Sarabhai). Others could not be identified.

From left: YJ Rao (fourth), Sarabhai, RD John, R Aravamudan (tenth), and HGS Murthy (eleventh). Others could not be identified.

The first rocket from Sriharikota Range (SHAR) took off on 9 August 1971.

Inauguration of Krishi Darshan, a TV programme meant exclusively for farmers. Sarabhai conceived of this programme to convince the Government that TV could be used to inform farmers of the latest developments in agriculture. In a sense, Krishi Darshan was a precursor to the Satellite Instructional Television Experiment (SITE) that was later conducted by ISRO jointly with NASA during 1975–76. Picture shows Sarabhai and Prime Minister Indira Gandhi with a farmer.

In September 1968, Sarabhai (left) signed an agreement with the NASA Administrator, Thomas O Paine, for jointly conducting the Satellite Instructional Television Experiment (SITE). Sarabhai did not live to see the experiment, which was conducted during 1975–76. SITE was described by Arthur C Clarke as, "the greatest communication experiment in history". Courtesy: NASA.



Satish Dhawan

The Dhawan Era

Introduction

ISRO's success with the Chandrayaan-1 mission to the Moon and the Mangalyaan mission to Mars has inspired many young people and given the nation a sense of justifiable pride. Now, Mangalyaan graces the new ₹2000 currency note issued by the Reserve Bank of India! In the midst of all the hype and euphoria surrounding such glamorous events, it is only proper to recall the gentle colossus who transformed Vikram Sarabhai's vision into the vibrant organisation that ISRO is today, namely, Satish Dhawan.

In an inspired move, Indira Gandhi, then Prime Minister of India, chose Satish Dhawan, Director of the Indian Institute of Science (IISc), Bangalore, to succeed Sarabhai, who had suddenly passed away in December 1971. But Dhawan did not take charge of the space programme immediately; he first completed his sabbatical at Caltech, USA, and after returning to India, took permission from the Governing Council of IISc to accept the PM's offer; he then met Indira Gandhi in June 1972. He persuaded her to create the Space Commission and the Department of Space (DOS) subsequent to which the President of India, VV Giri appointed Prime Minister Indira Gandhi as Minister of Space. In August 1972, Dhawan obtained a broad national consensus on the main objectives of the space programme through a national seminar held in Ahmedabad before taking over ISRO as its Chairman in September 1972. (It may be mentioned that this national seminar was originally planned by Sarabhai). In the interim period of January–September 1972, MGK Menon was the Chairman of ISRO.

One of the very first things that Dhawan did even before becoming the Chairman of ISRO was to persuade Brahm Prakash, the elderly metallurgist of international repute from the Atomic Energy Establishment, to take charge of all the space activities at Thumba.

Now, Dhawan was the Chairman of ISRO, Secretary, Department of Space, and Chairman, Space Commission, all rolled into one. Borrowed from the Atomic Energy programme, this concept of a single professional holding all the three offices was crucial to the success of the space programme. It ensured perfect harmony between the nation's space policies (the Commission), the R&D programmes (ISRO) and budgetary provisions (DOS). This arrangement still holds good today. At that time, ISRO was still an autonomous entity but Dhawan realised that for the organisation to deliver on its potential, it must be part of the Government. Against stiff opposition, he brought ISRO under the DOS. In this he was ably assisted by TN Seshan, the Additional Secretary, DOS. (Later, Seshan became the high-profile Chief Election Commissioner of India). The Prime Minister being in charge of space further helped matters.

The first meeting of the Space Commission was held on 10 July 1972 in New Delhi. Seen are: centre, facing the camera: Satish Dhawan (Chairman); on his left: MGK Menon (Member), PN Haksar (Member) and Brahm Prakash (Member). On the right of Dhawan: PN Dhar, Principal Secretary to the PM, IG Patel (Member for Finance) and MA Vellodi, Joint Secretary, DAE.

For a brief period following the sudden death of Sarabhai in 1971, MGK Menon was the Chairman of ISRO. Picture shows Menon laying the foundation stone for the Propellant Fuel Complex in the newly formed Vikram Sarabhai Space Centre (VSSC).

APJ Abdul Kalam briefing the Space Commission members in SHAR (8 August 1978). From left: Col N Pant, Satish Dhawan, Kalam, (not identified), Manmohan Singh, (partially seen, not identified), MGK Menon, K Narayana and R Jayamani. It is interesting to note that later, Kalam became the President of India and Manmohan Singh, the Prime Minister.

ISRO's biggest sounding rocket, RH-560, on the launcher in SHAR. The two persons standing akimbo are Satish Dhawan (left) and YJ Rao.

From left: Brahm Prakash (Director of VSSC, at the mike), S *Ramaseshan (of Indian Institute of Science, Bangalore) and Achutha Menon (Chief Minister of Kerala) at a seminar in VSSC.*

Birth of the Vikram Sarabhai Space Centre (VSSC)

The Space Commission met for the first time on 10 July 1972; the members present were: S Dhawan (Chairman), Brahm Prakash (Member), PN Haksar (Member), MGK Menon (Member) and IG Patel (Member for Finance). Also present was MA Vellodi (Joint Secretary, Department of Atomic Energy). The minutes read as follows:

"After welcoming the other Members of the Commission, Chairman suggested that since it was the first meeting of the Space Commission it would be appropriate to adopt a resolution placing on record its recognition of the outstanding contributions made by the late Dr Vikram Sarabhai in the field of space activities in the country. This was agreed to and it was decided that a draft resolution be circulated to the Members within the next few days for approval."

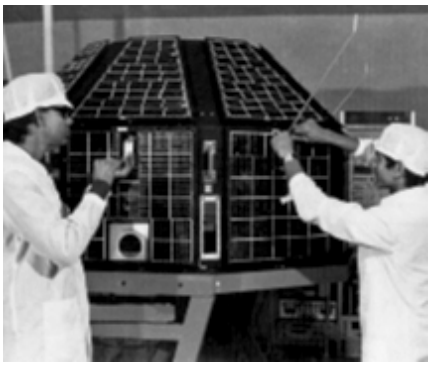
Consequently, all the different units functioning in Thumba, namely, the Space Science and Technology Centre, the Rocket Propellant Plant, the Rocket Fabrication Facility and the Thumba Equatorial Rocket Launching Station were combined and named as the Vikram Sarabhai Space Centre (VSSC). And Brahm Prakash was appointed as its Director.

Signing the Aryabhata agreement are BN Petrov (seated left) and Satish Dhawan (right). Standing from right: UR Rao, MA Vellodi, PD Bhavsar, A Bogomolov, B Novikov, V Kovtunenko and (not identified).

Industrial sheds in Peenya, Bangalore, where Aryabhata was designed and developed under the guidance of UR Rao.

Aryabhata was helicopter-borne for testing the telemetry system in Sriharikota Range (SHAR).

The Bhaskara team in the USSR. The satellite mounted on the launch vehicle is seen in the background.



Above: The Rohini satellite being assembled. This was launched by India's first launch vehicle, SLV-3.

Innovations of Dhawan

The setting up of ISRO HQ in Bangalore, staffed by a set of young and dedicated professionals hand-picked by Dhawan himself, completed the process of linking ISRO programmes and projects with decision-makers and sources of funds. This particular architecture that Dhawan put together was original and innovative. ISRO's continuing success is visible proof of this robust Dhawan design.

Under the leadership of Dhawan and Brahm Prakash, ISRO pioneered a new way of managing complex projects. In this arrangement, a single Project Management Team (PMT), under a Project Director, was made responsible for specifications, planning, follow up, vehicle integration and check-out. The sub-contracts, which were at the component and subsystem level, were awarded to various R&D groups of ISRO Centres, and industries. The point to be noted is that the Project Director may even be junior, hierarchically speaking, to the Chiefs of the R&D groups. (In management jargon, this concept can described as follows: the integration of domain expertise with project deliverables under a project director was achieved without alienating the top functional and domain heads). An outstanding example of this was the choice of APJ Abdul Kalam as the Project Director of the SLV-3 project, which at that time was the most prestigious and complex project of ISRO. Hierarchically, Kalam was a relatively junior engineer in VSSC. Dhawan also ensured total transparency in project management by involving leading professionals outside ISRO in the technical reviews of its projects.

From the beginning, Dhawan insisted on a significant role for indigenous industry in the projects of ISRO. Today, hundreds of industrial units, both in the public and the private sectors, manufacture a wide range of space-quality hardware for ISRO.

The early days of the Dhawan era saw many failures. Through all of these turbulent times, Dhawan never lost faith in ISRO's capabilities or in the talent of Indian engineers. He took personal responsibility for failure but when success came, he always attributed it to ISRO and his colleagues. Thus, when the first flight of the SLV-3 in 1979 failed, Dhawan faced the press. When the second flight succeeded, Dhawan kept himself in the background while Kalam spoke to the press. With this kind of leadership, engineers and scientists in ISRO were never afraid to face honest failures.

Dhawan created three committees to ensure the participation of all the stakeholders in planning ISRO missions. The INSAT Coordination Committee (ICC) has Secretaries of various Departments such as Telecom, Information and Broadcasting, and Science and Technology as members. Thus, while defining the payloads for INSAT communication satellites, the needs of these Departments are taken into account. The second is the Planning Committee of the National Natural Resources Management System

(PC-NNRMS). NNRMS was conceived of as a system in which conventional and remote sensing technologies could be combined to provide reliable information to the Government Departments dealing with the nation's natural resources. Secretaries of these Departments are members of NNRMS while the DOS acts as the nodal agency. It is headed by a Member of the Planning Commission. The third committee, known as the Advisory Committee on Space Sciences (ADCOS), deals with the science missions of ISRO and has the leading space scientists of the country as its Members.

These three committees, while providing mature guidance, also ensured transparency about what ISRO does in these fields. Most of what ISRO does so well today – the IRS and INSAT systems with their linked PSLV and GSLV launchers including the Chandrayaan and Mangalyaan missions, are the outcomes of these carefully thought-out processes.

Dhawan treated employee unions as partners, rather than as adversaries, and created the Joint Consultative Machinery (JCM), which provided an official forum for the unions to interact with the Management. This was a first in the R&D organisations of the country.

The Man

Handsome and simple, Dhawan never seemed to realise the impact his personality had on others. He was very good with his hands and could repair and fix many gadgets.

He respected and worked closely with workers and technicians in the pursuit of his many research interests. Many of them reciprocated his genuine interest by adoring him and doing anything to help him. He had a great interest in issues of war and peace and the role that science and technology could play in resolving conflicts between nations. At ISRO, he set up one of the earliest think tanks in the country to deal with these issues. After retiring as Chairman, ISRO, he combined his interests in aeronautics and the environment to study the flight of birds. He traversed the backwaters of Pulicat Lake in Sriharikota, documenting the flight of birds. His monograph on bird flight is a classic. Many of the drawings of birds that appear in this monograph were sketched by Dhawan himself.

“If I have to choose one word that would define his personality, it would be integrity,” wrote Yash Pal. This is how Narasimha and Abdul Kalam sum him up: “Professor Dhawan in his professional career has been engineer, teacher, research scientist, technologist, manager, leader and adviser – often all at the same time! His great human qualities, combining intense personal charm with a deep commitment to social values and an extraordinary objectivity in management, have led several generations of students, colleagues and administrators to efforts that they would otherwise not have taken”.

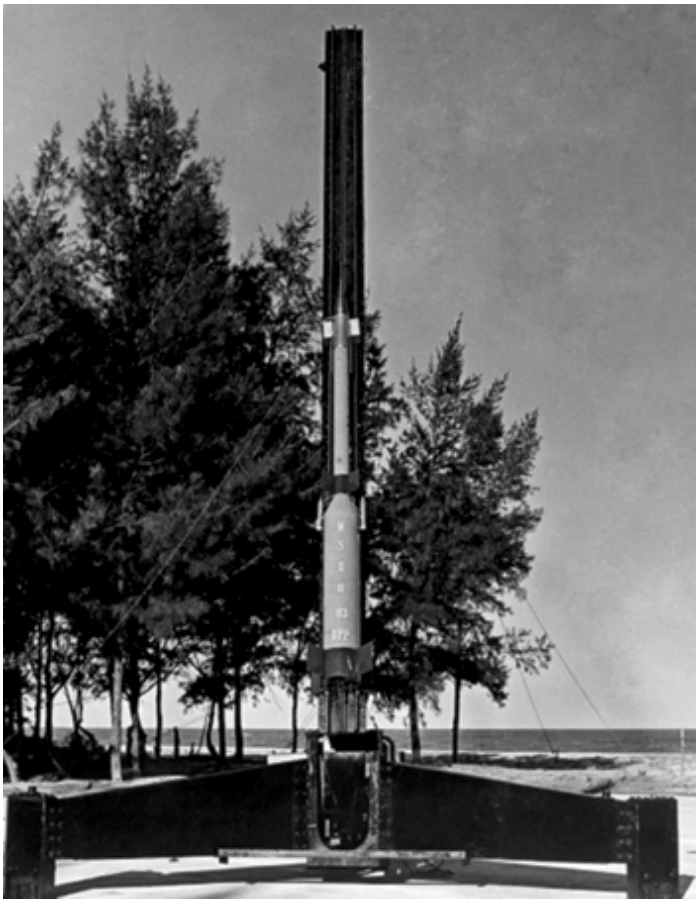
Maybe there is no better description of him than what Shakespeare wrote:

His life was gentle, and the elements

So mix’d in him that Nature might stand up

And say to all the world. “This was a man!”

★★★



Menaka sounding rocket. It had an unusual combination of a radial burning booster and an end burning sustainer. Later, its development was abandoned.

From left: Prime Minister Indira Gandhi, EV Chitnis and Yash Pal at the Space Application Centre, Ahmedabad, during the days of Satellite Instructional Television Experiment (SITE).

People watching community TV organised during SITE.

Using theatre to convey socially relevant messages to remote villages through satellites (Jhabua Project).

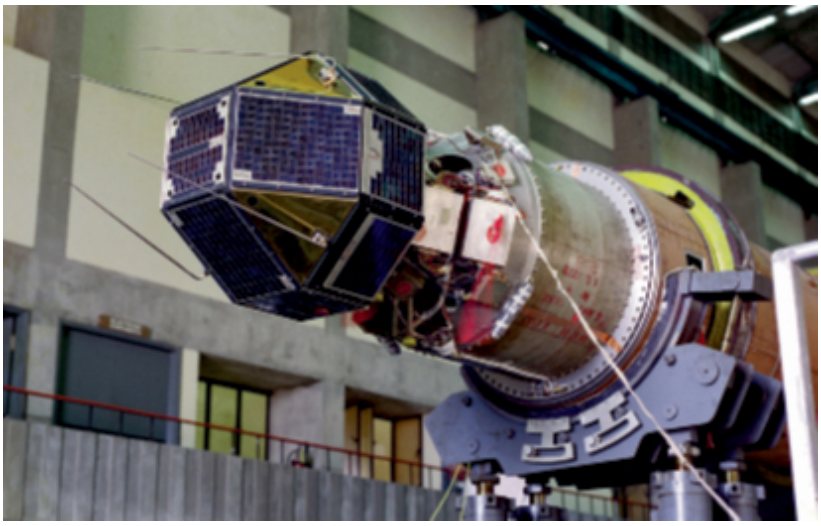
Conveying messages through folk tales during a SITE programme.

Satellite Telecommunication Experimental Project (STEP) was conducted under the direction of Col N Pant during 1977–79. For this, the Franco-German satellite, Symphonie, was used to gain experience in digital communication involving Time Division Multiple Access (TDMA), spread spectrum and facsimile transmission.

From left: Chairman, ISRO, Satish Dhawan, (not identified), SC Gupta, M Nageswara Rao, KPM Bhatt, Sitapati Rao and N Vedachalam. The hardware on display consisted of disassembled parts of: (1) a three-axis freedom hydrostatic air bearing and (2) the precision parts of an MRG 74 miniature rate gyroscope of SLV-3 vintage, but it served ISRO well till the GSLV.

George Joseph (second from right) briefing Yash Pal (seated) and Satish Dhawan (extreme left) about an aircraft-mounted multispectral scanner.

Prime Minister Morarji Desai (middle) being received at VSSC *by Brahm Prakash (right). Back to camera is Dhawan.*



The Rohini satellite mounted on the fourth stage of the SLV-3, India's first satellite launch vehicle.

The fully assembled SLV-3 being transported to the launch pad.

SLV-3 on the launch pad.

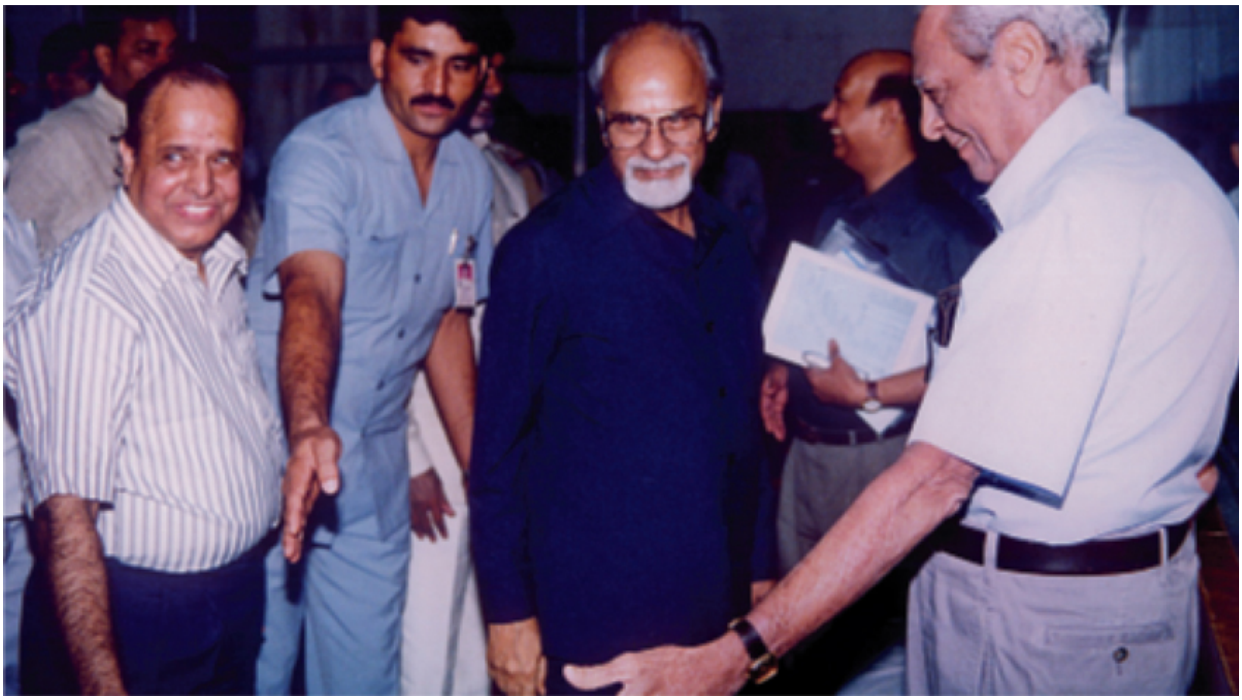
Celebrating the success of SLV-3 at the Duty Officer's desk, VSSC (18 July 1980).

Ariane Passenger Payload Experiment (APPLE) mounted on a bullock cart to provide a non-magnetic environment and to conduct an antenna test in an open field to remedy a TTC link problem. The American magazine, Newsweek, described this as a collision of cultures in which, between the tail of the ox and the sophisticated APPLE, lay centuries. The problem was solved in about five hours at a cost of Rs.150 for hiring the cart!

APPLE was sandwiched between Meteosat on top and Capsule Ariane Technologique below. The French team in the foreground.

Dhawan (blue shirt) visiting Composites facility at Vattiyoorkavu, Trivandrum. Also present were VR Gowariker (bearded) and Rajaram Nagappa (partially seen behind Gowariker). CR Sathya is seen on the right of Dhawan.

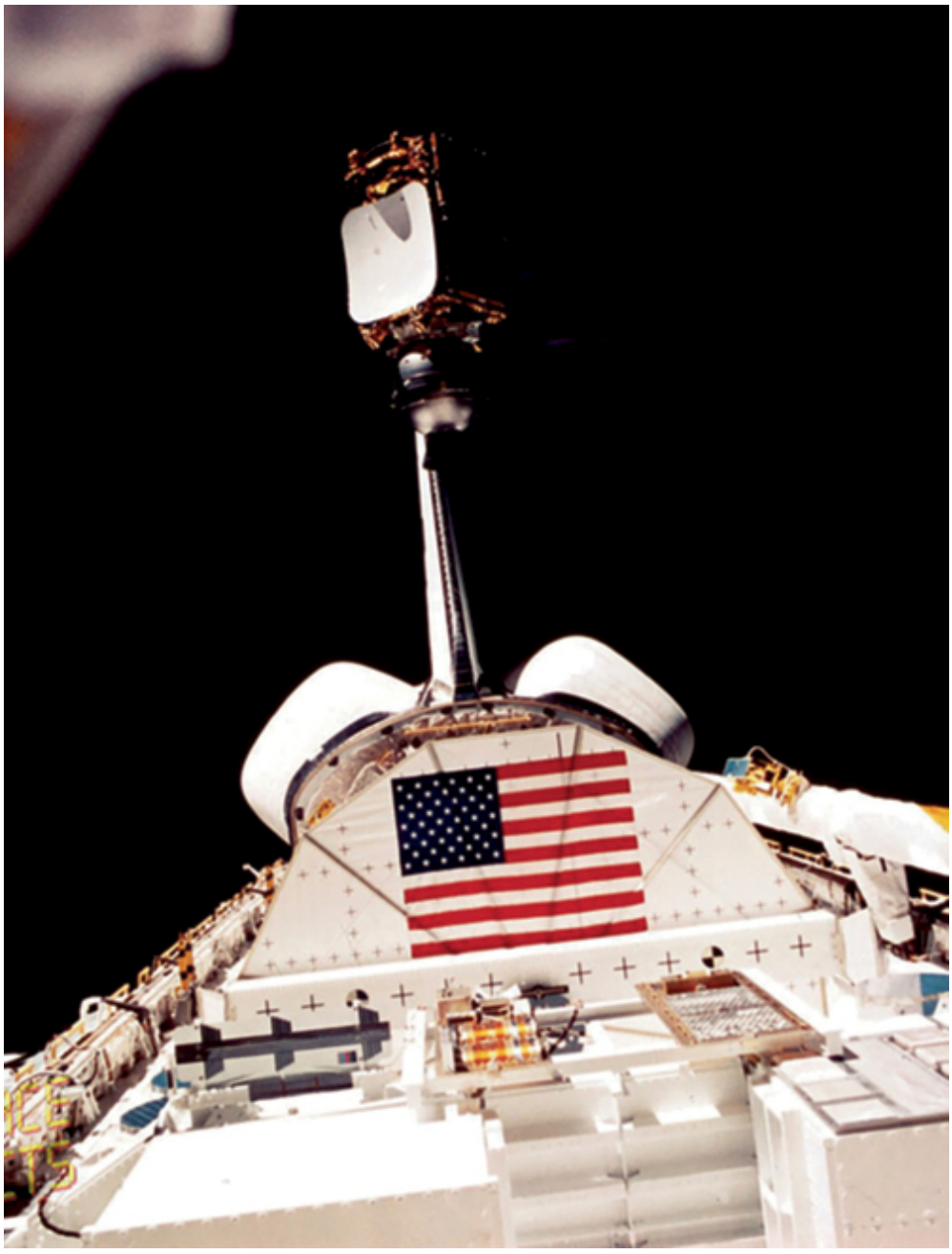
Chairman Dhawan (fourth from right) surveys the area near Mahendragiri in Tamil Nadu for locating the test set-up for liquid propulsion systems. At extreme right is AE Muthunayagam, and to the right of Dhawan are RD John and VR Gowariker.



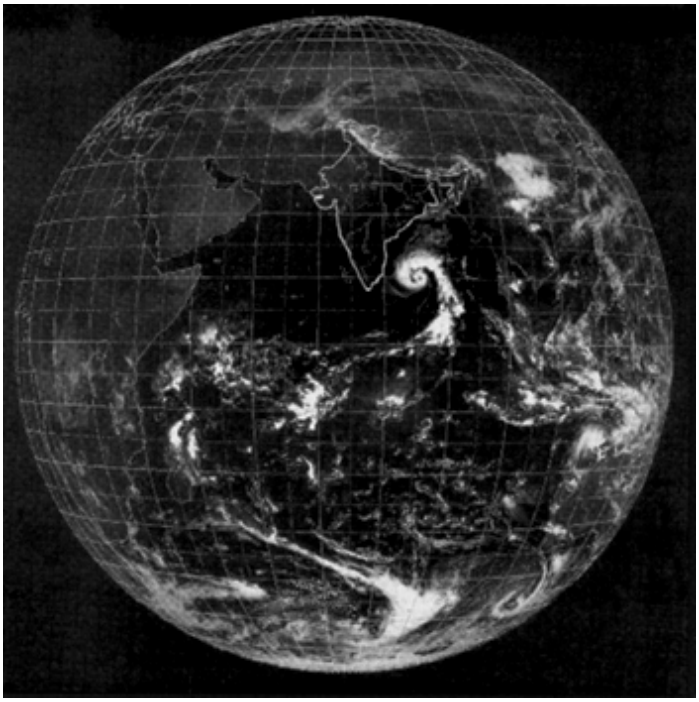
Three former chiefs of ISRO with Prime Minister IK Gujral (bearded). From right: Satish Dhawan, UR Rao and far left: K Kasturirangan.

Indira Gandhi, after visiting the satellite centre in Peenya, Bangalore. Seen from left are: TN Seshan (extreme left), UR Rao (fourth), Satish Dhawan, Indira Gandhi and Mrs. Nalini Dhawan (extreme right). Also seen are Mrs.

Rao and daughter. Seshan, as Joint Secretary of Department of Space, was instrumental in bringing ISRO under the Government of India. Later, Seshan became the high-profile Chief Election Commissioner of India.



INSAT-1B, the second in the INSAT-1 series, was launched using the Space Transportation System Orbiter "Challenger" of the USA on 30 August 1983. Courtesy: NASA.



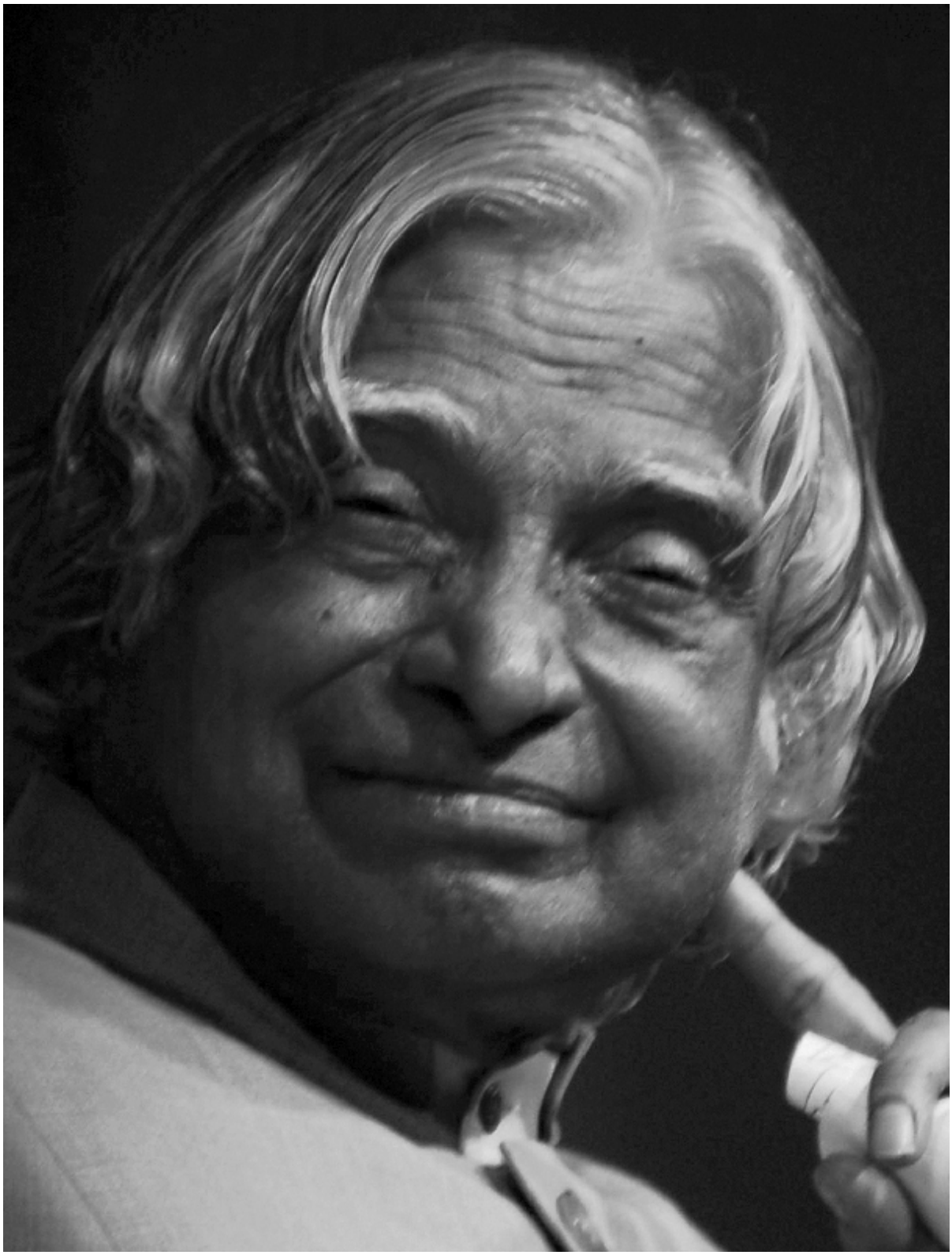
Full-disc Earth as seen by INSAT-1B. A cyclone system to the east of India is clearly seen.

Originally established as part of the INSAT-1 ground segment, Mission Control Facility (MCF) of ISRO is used to track, monitor and control all the

geostationary satellites of ISRO.

While Vikram Sarabhai laid the foundation for ISRO, Satish Dhawan was the main architect who transformed ISRO into a technological giant in the country. Here, Dhawan is seen addressing the staff of VSSC on the eve of his retirement as Chairman of ISRO and Secretary, Department of Space. He retired in 1984.

Dhawan takes leave in traditional manner. Also seen is VR Gowariker (Director, VSSC).



APJ Abdul Kalam

Rockets of ISRO

Introduction

On 15 February 2017, ISRO created history by launching 104 satellites in one go, using the Polar Satellite Launch Vehicle (PSLV). Well, as numbers go, it was undoubtedly a record, but the real significance of that feat was the confidence reposed by foreign countries, including the USA, in the capability of ISRO. This success was the result of meticulous planning and flawless execution of the mission by ISRO. PSLV is by no means the most powerful rocket in the world, nor, for that matter, even in ISRO'S armour. Yet, the story of PSLV is, in a sense, the story of rocketry in ISRO, which starts with sounding rockets.

Sounding rocket RH-200 on the launch pad.

Left: Single-stage RH-300 in flight.

Middle: RH-560 is the most powerful two-stage sounding rocket of ISRO.

Right: RH-560 in flight

Old or young, heads turn skywards whenever a rocket takes off!

Sounding rockets

These are relatively small rockets, generally but not exclusively, used to probe (that is, to sound) the upper regions of the atmosphere. Usually, they have one or two stages powered by solid propellants and are unguided, with fins providing stability. They go up to specified altitudes and then fall back; during the upward or downward trajectories, they release payloads (for example, a scientific experiment) designed by scientists. They are also used to flight-test packages developed for launch vehicles. They cannot be used to orbit satellites.

The main features of sounding rockets that appeal to scientists are the simplicity of hardware and low cost. They can be assembled at short notice

and several of them can be launched in a single day. They provide the cheapest means of introducing students to space research.

Having experimented with a large number of prototypes, ISRO had zeroed in on three operational sounding rockets (an operational system is one that carries out its intended function routinely and efficiently). These are designated as: RH-200, RH-300 Mk II and RH-560, where EH stands for Rohini and the numbers represent the largest diameter of the rocket in millimetres. Their main features are tabulated below. All numbers are approximate.

Several hundred Rohini rockets have been launched by ISRO, which had supplied the RH-300 Mk II to Norway.

Payload

The word payload often occurs in this book. For a sounding rocket, the payload is the weight of the scientific or technological package it lifts to a specified height. For a launch vehicle, it is the weight of the satellite (or probe) it injects into a specified orbit. For a satellite, it depends on the mission; for remote sensing or Earth observation satellites, the payloads are the imaging systems (cameras) and for communication satellites, they are the transponders needed for telecommunications, TV broadcast, etc. Sometimes a communication satellite (for example, INSAT) may also carry a radiometer that takes pictures of cloud cover. It is worth noting that the payload of a launch vehicle is a small fraction of the lift-off weight of the rocket

Launch vehicles

In common parlance, ‘rocket science’ connotes something very complex and difficult. This is literally true of launch vehicles, which are rockets that can orbit satellites and send probes to explore planets and interplanetary space. Compared to sounding rockets, they are massive and complex, needing expertise in over a dozen fields of science and engineering. Unlike sounding rockets, they continuously gain the speed necessary to launch satellites into specific orbits. For example, a satellite in an orbit at an altitude of 600 km must have a speed of over 27,000 kilometres per hour. No object near the

Earth's surface can travel at those speeds without burning up, just as meteors do in the atmosphere. Even at that speed, the launch vehicle must be controlled delicately to ensure mission success.

They carry hundreds of tonnes of potentially explosive chemicals known as propellants, which means rocketry is a risky business.

"There are a thousand things that can happen when you go light a rocket engine, and only one of them is good", said Tom Mueller of the company, SpaceX.

SLV-3, the first launch vehicle of ISRO

For all of the above reasons, when ISRO successfully launched the SLV-3 on 18 July 1980, the world stood up and took notice. By world standards, the SLV-3 was tiny for it could orbit only a 35-kg satellite. Even so, it broke the monopoly of the advanced nations in space technology! With a length of 22 m, at lift-off, the SLV-3 weighed about 17 tonnes. APJ Abdul Kalam, the Project Director of SLV-3, became a household name in the country. SLV-3 was a good learning experience in launch vehicle technology for ISRO.

Augmented Satellite Launch Vehicle (ASLV)

Everyone knew that SLV-3 was not a vehicle for orbiting operational satellites. For that, ISRO had set its sights on the PSLV, the Polar Satellite Launch Vehicle, with the capability of orbiting a 1000-kg satellite into sun-synchronous orbit. (This is an orbit in which the satellite crosses the equator at a fixed local time – a feature that is useful in remote sensing). But the technological jump, including the scaling up from SLV-3 to PSLV, was too big to be comfortable for a fledgling space programme. Enter ASLV, the Augmented Satellite Launch Vehicle, which ISRO conceived of as a technological bridge between SLV-3 and PSLV.

By adding two strap-ons (side rockets) to the SLV-3, each with the same propulsive power as the first stage of the SLV-3, it was thought that the satellite weight could be trebled. And quite a few new technologies like closed-loop guidance (which would ensure precision insertion of the satellite

into orbit) and bulbous heat shield (which would accommodate bigger satellites), could also be proven before their eventual deployment in PSLV. And all this could be done for a pittance of a budget and within a couple years – or so it was thought.

But the first two flights of the ASLV failed, ending up in the Bay of Bengal and sending shock waves through ISRO. For a nation that takes a loss in a cricket match as a national catastrophe, these failures meant loss of prestige, but the media played a responsible role. The two failures even seemed to threaten the confidence of the teams developing the PSLV. The failure analysis of the ASLV turned out to be the most gruelling, yet most rewarding, Job ever done by ISRO (including some experts from outside). To sum it up in one sentence: if through the SLV-3 experience, ISRO learnt the alphabet of launch vehicle design, through ASLV, it learnt the grammar.

The third flight of the ASLV on 22 May 1992 was successful, validating the lessons learnt through two successive failures. Thus ended the experimental phase of launch vehicle development in ISRO. Next, of course, was the operational phase.

Polar Satellite Launch Vehicle (PSLV)

On 14 November 2008, the Moon impact probe with the national tricolour and other scientific Instruments detached from the Chandrayaan-1 orbiting spacecraft and, as planned, crash-landed on the lunar surface. Befittingly, the day also marked the birth anniversary of jawaharlal Nehru, the first Prime Minister of India, with whose help Vikram Sarabhai and Homi Bhabha launched the Indian space programme in 1963. Later analysis of Chandrayaan-1 data led to the discovery of water on the Moon. On 24 September 2014, the Mars Orbiter Mission (MOM), also known as Mangalyaan, inserted the probe into an orbit around Mars. Both these historic events have created a sense of pride in the people of India, and PSLV, the rocket responsible for both missions, has become a household name, and once again ISRO has become the darling of India. In 2017, PSLV drew the attention of the world when it orbited 104 satellites in a meticulously planned and executed mission. A world record!

Developed in the 1990s, PSLV has undergone substantial improvements, and both the lunar and Mars missions were launched by its most powerful variant, known as PSLV-XL. In this nomenclature, XL stands for the extended length of the strap-ons, each of which now carries 12.8 tonnes of propellant instead of the original 9 tonnes.

The story of PSLV has two distinct phases: developmental and operational. Starting in 1982, the development phase lasted till 1995. During this period, three launches were made, of which the first in 1993 failed due to a software error. After this, the PSLV has never looked back. The operational phase has seen more than 45 successively successful launches.

How many years did it take ISRO to develop the PSLV? What were the problems faced during development? How many people worked for it? How much did it cost to develop it? What new infrastructure was created for the PSLV? Questions such as these are of interest to all people and, of course, we can give detailed answers, but then a coffee table book is not the proper medium for such an exercise. We would need a huge technical tome. Nevertheless, we offer below somewhat simple answers to some of these questions.

- Counting from the date the Government sanction was granted for the Project, it took about 11 years before the first PSLV could be launched.
- Not counting people in about 150 industries and several R&D institutions who contributed to the project, within ISRO itself, about 3000 technical people worked directly for the PSLV. (Some of them concurrently worked on other projects of ISRO).
- In 1993, soon after the first developmental flight of the PSLV failed, the Chairman of ISRO, UR Rao wrote: “The cost of PSLV is only about Rs. 45 crores. The total cost of PSLV Project is Rs. 415 crores which includes two rocket flights and all the infrastructure created as well as the cost of development and tests. The cost of two PSLV rocket flights and essential standby is about Rs.100 crores. The rest is towards the cost of various infrastructure created at SHAR (Sriharikota), Valiamala (near Trivandrum) and Mahendragiri (in Tamil Nadu). All these will be

available not only for the PSLV programme but also for the GSLV programme.”

It should be noted that a launch vehicle can be used for different missions. The only thing that changes is the payload mass. PSLV has been used not only for polar missions but also for Geosynchronous Transfer Orbit (GTO), Moon and Mars missions and for the recovery of a satellite too.

Geosynchronous Satellite Launch Vehicle (GSLV)

ISRO was aware of the limitations of PSLV even before its first launch. PSLV lacks the power to launch ISRO’s own communication satellite, weighing 2000 kg or more. So ISRO had to look elsewhere to launch such heavy satellites.

To overcome this limitation, a three-stage GSLV (for historical reasons, also referred to as GSLV Mk II) was conceived. The first two stages of GSLV have PSLV heritage but the third and final stage has cryogenic propulsion for which ISRO did not have the technology. Cryogenic propulsion uses liquid hydrogen (LH_2) as the fuel and liquid oxygen (LOX) as the oxidiser. Now LH_2 boils at 20 K (that is, 253°C below zero) and LOX at 90 K (that is, 183°C below zero). These extremely low temperatures (hence the name cryogenic) make it difficult to even produce and handle these propellants. Moreover, LH_2 is highly explosive and has low density, which means one has to carry large volumes of it. Yet cryogenic propulsion is used because of its high specific impulse, which is a measure of the efficiency of the propulsion system. The specific impulse (expressed in units of second) of the cryogenic propulsion system is 450–460 s as compared with 260–280 s of solid propulsion and 280–320 s of liquid propulsion systems. Even the technologically advanced nations had taken 10–15 years to develop cryogenic propulsion systems.

As ISRO was mulling over all its options for developing the GSLV, the Russian space agency, Glavkosmos (GK), expressed its willingness to cooperate with ISRO in jointly developing the Cryogenic Stage (CS) for GSLV. For a very reasonable cost, GK would supply two flight cryo-stages and transfer the technology for the same by training ISRO engineers at

Russian facilities. So the contract between GK and ISRO was signed in January 1991.

Things were going smoothly as planned but suddenly, 15 months after the contract was signed, the American Government raised an objection, claiming that the contract violated the MTCR (Missile Technology Control Regime) provisions, and they imposed sanctions against ISRO and GK. Unfortunately, this ruckus raised by the USA coincided with unprecedented geo-political tectonic shifts that resulted in the dissolution of the Soviet Union and the birth of a new Russia. Consequently, the technology transfer could not take place and the contract was renegotiated. The net result was that the development of cryogenic propulsion systems by ISRO was delayed.

ISRO adopted a two-pronged approach: first, it indigenously produced the cryo-stage of Russian design, and second, it designed and developed a cryo-engine (CE 20) and stage (C 25) of its own design, based on a different principle. GSLV Mk III (also referred to as LVM3), described in the next section, is powered by C 25. The main features of the GSLV are – Height: 49.13 m, Lift-off mass: 414.75 tonnes, Payload to Geosynchronous Transfer Orbit (GTO): 2500 kg.

GSLV Mk III

On 5 June 2017, ISRO successfully launched GSAT-19, a communication satellite weighing 3136 kg, into a Geosynchronous Transfer Orbit (GTO), using the launch vehicle GSLV Mk III. This is the vehicle that ISRO had been working on for over a decade and a half. Once GSLV Mk III became operational, ISRO did not need to approach anyone else for launching any of its satellites.

This is a brand-new, world-class vehicle that demonstrates ISRO’s mastery over cryogenic technology and clustering of liquid engines. It has two giant strap-ons, each carrying 200 tonnes of solid propellant and hugging a core liquid booster comprising two clustered Vikas engines with a propellant load of 116 tonnes. These Vikas engines have PSLV and GSLV heritage. The third stage is ISRO’s own cryo-stage, C 25, with 28 tonnes of cryo-propellants, liquid oxygen and liquid hydrogen. (The cryo-engine is

designated as CE 20). It is worth emphasising that CE 20 is based on a gas generator cycle unlike the Russian-supplied one that was based on the staged combustion cycle. At lift-off, the rocket stood 43.5 m tall, with a core diameter of 4 m and weighed 640 tonnes.

Whether it is pair-casting of the strap-on solid motor segments or Ogive-shaped payload fairings (heat shield) or the lithium–ion batteries in the equipment bay, this rocket incorporates state-of-the-art features. (Pair-casting was carried out for ASLV too).

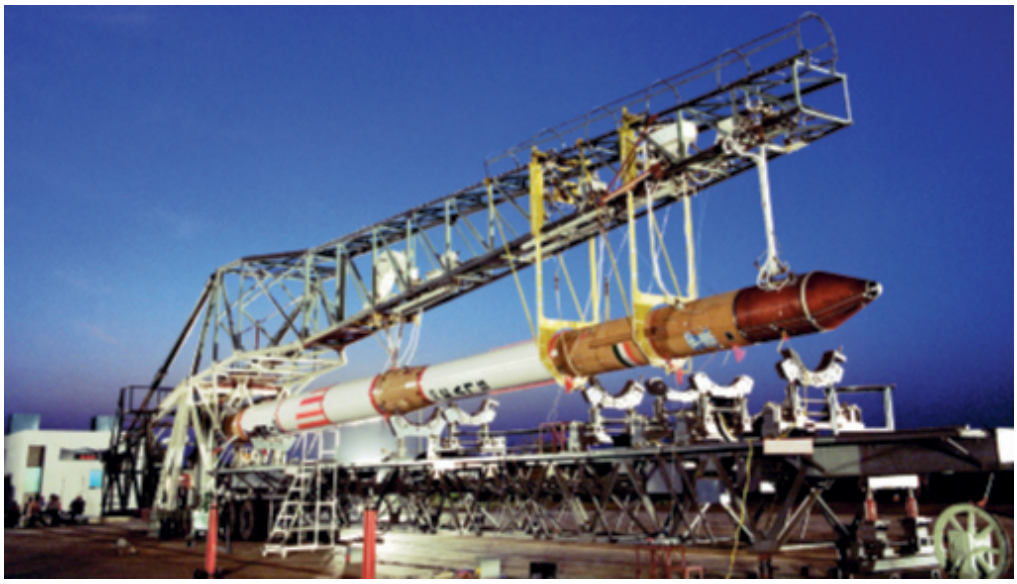
Reusable Launch Vehicle Technology Demonstrator in flight from Sriharikota island, the first step towards developing low-cost access to space

(23 May 2016).

SCRAMJET engine technology demonstrator in flight, the first step in developing air-breathing technology which uses atmospheric oxygen for propulsion (28 August 2016).

During integration of the SLV-3 in Sriharikota. Satish Dhawan flanked by S Srinivasan (left) and APJ Abdul Kalam,

Various parts of the SLV-3. All the stages would be electrically connected and tested before flight.



SLV-3 was the only launch vehicle of ISRO that was horizontally integrated and then hauled up into the vertical position before launch.

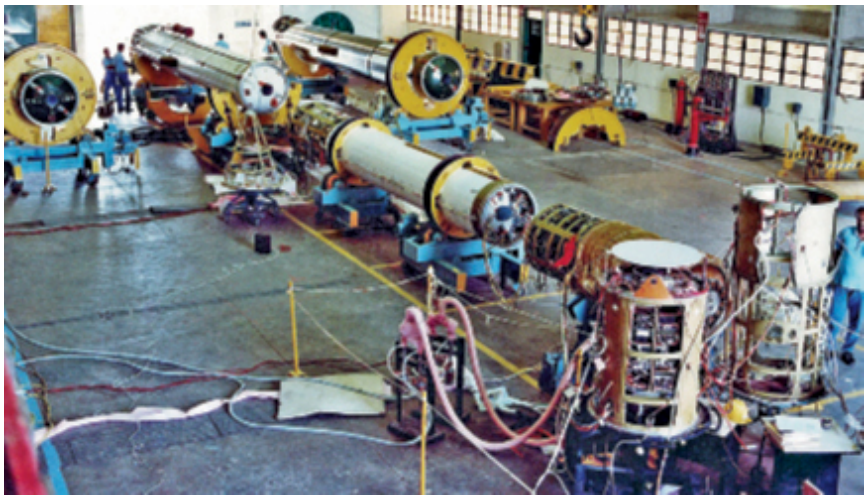
A group photograph taken at VSSC during SLV-3 times. Sitting (from left): AE Muthunayagam, SC Gupta, VR Gowariker, APJ Abdul Kalam, Satish Dhawan, Brahm Prakash, MR Kurup, D Easwaradas and R Aravamudan. Middle row (from left): TS Ram, Anantharam, N Vedachalam, V Sudhakar, BK Sarkar, K Sudhakara Rao, MK Abdul Majeed, EVS Namboodiri, G Madhavan Nair, VP Kulkarni, DS Rane and S Ramanath. Last row (from left): BC Pillai, T Pillai, CR Sathya, A Sivathanu Pillai, Sridharan Das, US

Singh, MSRDev, VP Sandlas, D Sasikumar, S Srinivasan, Sundararajan, MC Mathur, R Rajaram Nagappa, RS Bhute and Supramaniane.

First successful flight of SLV-3 (18 July 1980).

Name of rocket	RH-200	RH-300 Mk II	RH-560 Mk II
Payload, kg	10	60	100
Altitude reachable, km	65	130	470
Purpose	Meteorology	Aeronomy*	Aeronomy*

** Aeronomy is the study of the physics and chemistry of the upper regions of the atmosphere.*



Different stages of the ASLV in the Vehicle Assembly Building.

Sharing a lighter moment; from left: MSR Dev, R Narayanan, SC Gupta, Rajaratnam, VR Gowariker and Satish Dhawan.

Fully integrated ASLV on the launch pad.

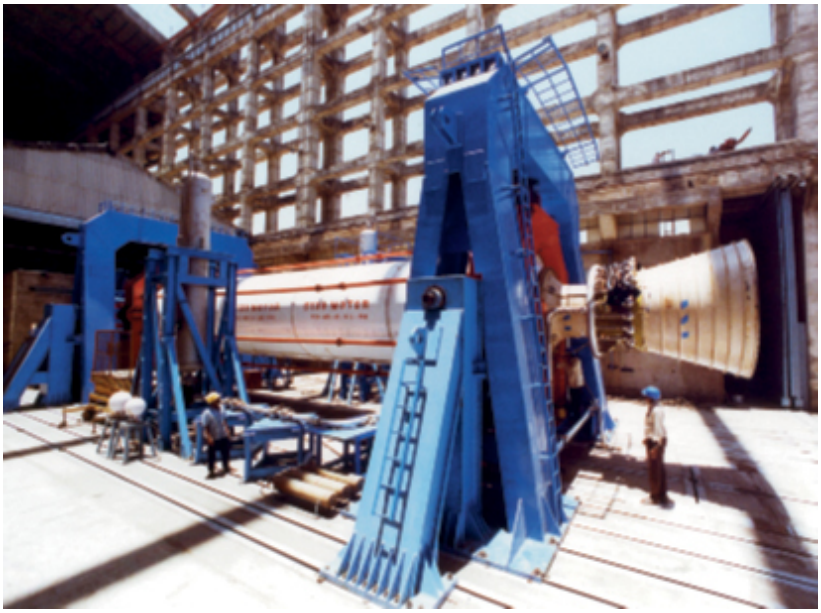
Side view of the ASLV caught along with its reflection in water.

ASLV in flight.

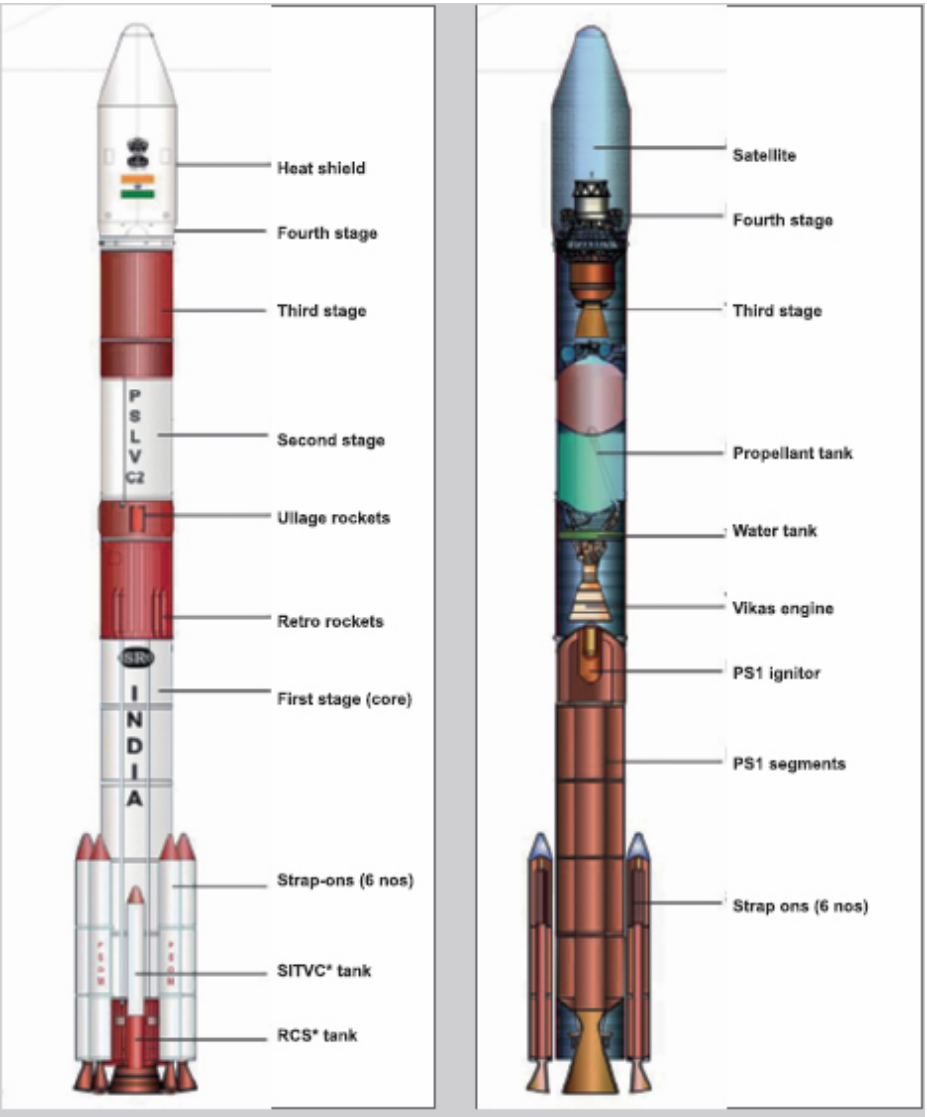
VR Gowariker congratulating MSR Dev after the successful flight of the ASLV.

SC Gupta (extreme left) handing over the first batch of NiCad batteries to N Pant, Director, ISAC. Also seen are VP Kulkarni and Gopinath Pai.

A view of the chemical laboratory in VSSC. One of the very first rocket technologies mastered by ISRO was solid propellants.



The PSLV first-stage motor on the static test stand, Sriharikota.



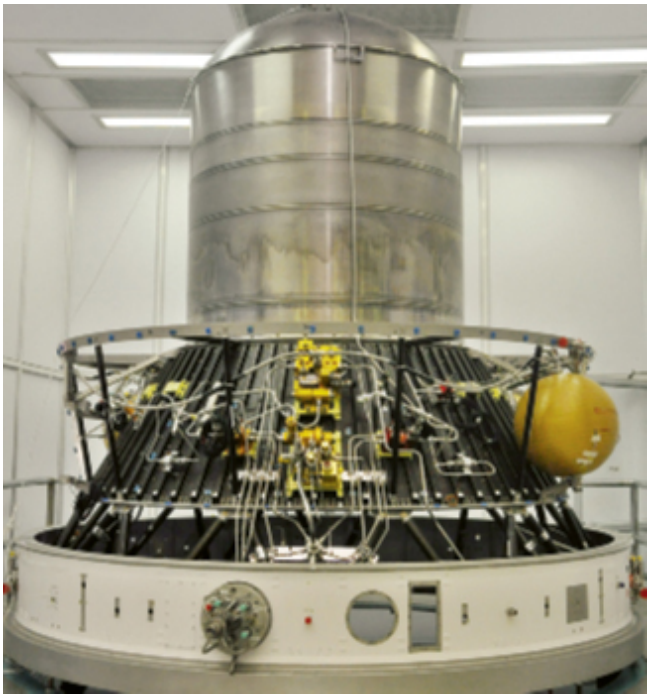
Picture showing the main parts of a launch vehicle (PSLV)

**SITVC: Secondary Injunction Thrust Vector Control, RCS: Reaction Control System*

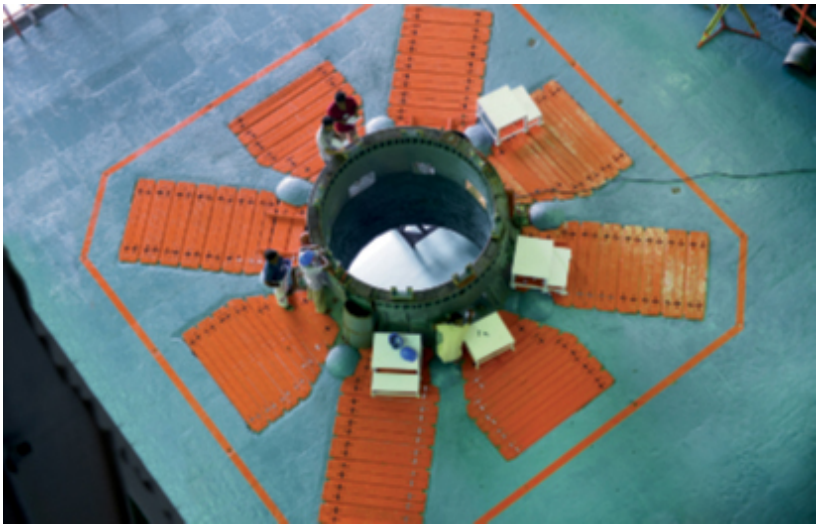
The PSLV booster firing from the static test bed. It contains 139 tonnes of solid propellant, all of which burns in about 100 seconds. This powers the first stage of the PSLV.

The PSLV second-stage liquid engine (Vikas) under hot test.

The PSLV third-stage composite motor case under inspection.

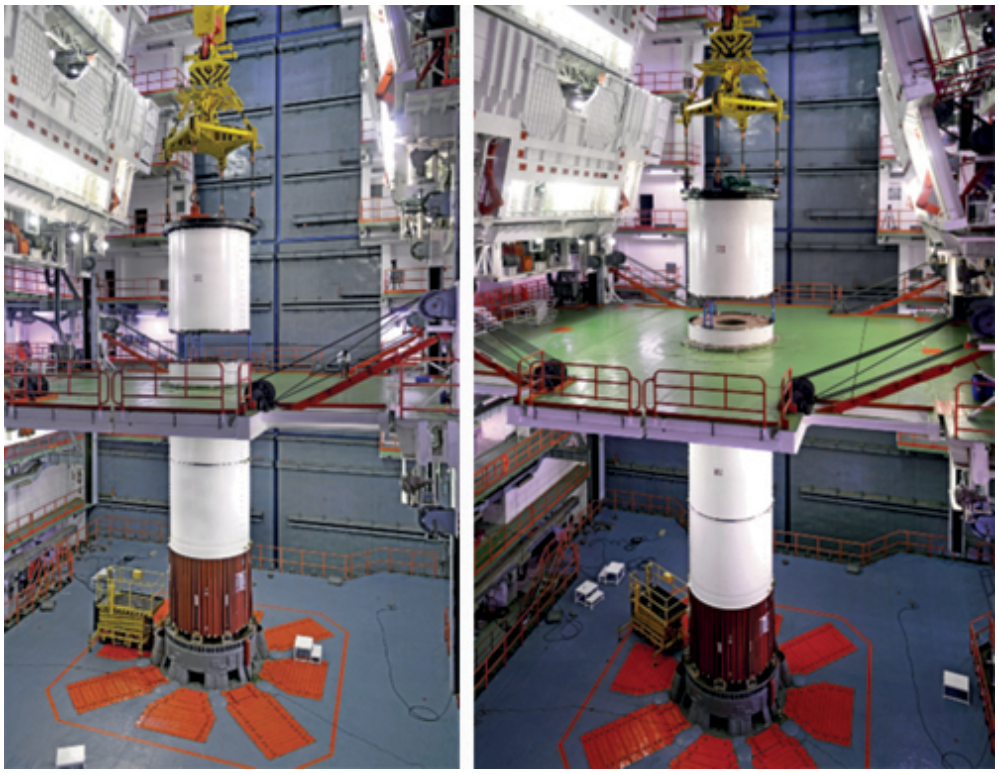


The PSLV fourth stage.



A vehicle such as the PSLV takes about 10 years to design and develop. It takes weeks to assemble, while the flight itself lasts for about 20 minutes. The following sequence of pictures shows the various stages of PSLV assembly, known as integration.

The first stage of the PSLV comprises a core motor of 139 tonnes of solid propellant and six smaller side rockets, known as strap-Ons, each carrying 12 tonnes of propellant. Pictures show the integration of the first stage.



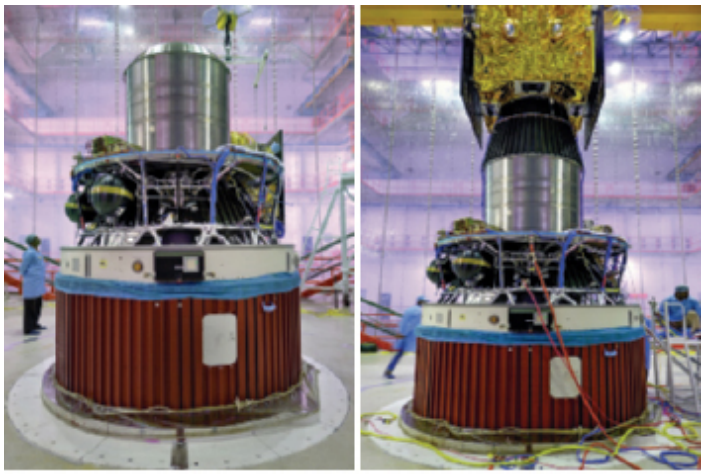
All the five segments of the core motor are being integrated.

The last segment of the core motor is being integrated.

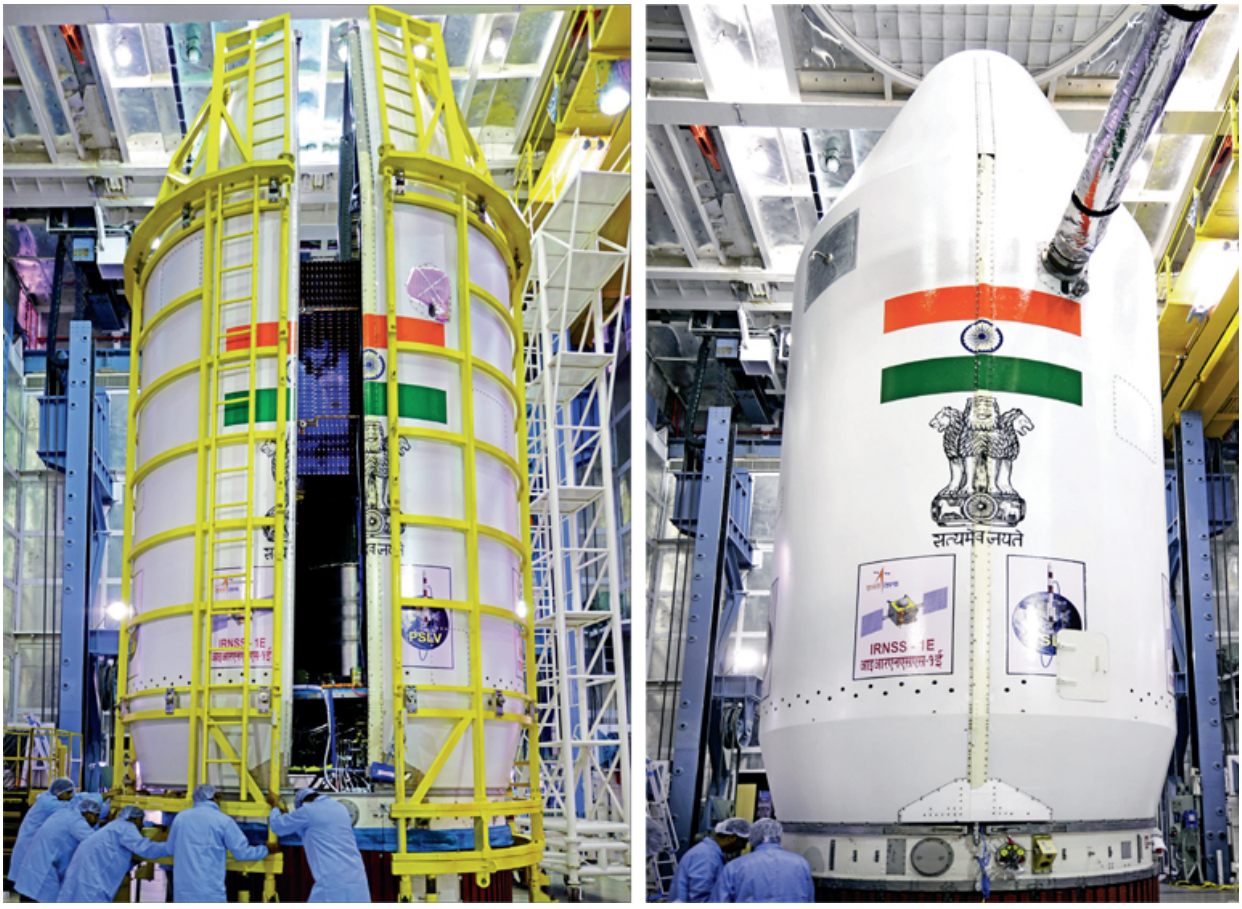
After assembly of the core motor, the ignitor, which by itself is a small rocket, is being inserted into the core.

Strap-ons being attached.

With the assembly of the first stage complete, the fully integrated second stage is mated with the first stage.



The third and fourth stages, along with the satellite, are being integrated.



Assembling the heat shield from two halves completes integration. The heat shield protects the satellite during the rocket's ascent in the atmosphere.

With the fully assembled PSLV on it, the mobile launch pedestal leaves the Vehicle Assembly Building. Typical vehicle specification – Height: 44 m, Lift-off mass: 320 tonnes, Payload: 1750 kg in sun-synchronous polar orbit.

A panoramic view with PSLV on the second launch pad. The four tall towers surrounding the launch pad are part of the lightning protection system.

Close-up view of the PSLV on the second launch pad.

PSLV lift-off from the first launch pad.

PSLV lift-off from the first launch pad, a close-up view.

Celebrating the first successful launch of PSLV. Project Director G Madhavan Nair (folded hands) acknowledging greetings from colleagues.

MYS Prasad addressing colleagues after the successful launch of PSLV C12. Also seen from left: PS Veeraraghavan, K Radhakrishnan, George Koshy, TK Alex, S Ramakrishnan, G Madhavan Nair and MC Dathan.

People watch a launch at Sriharikota, however precarious the perch may be!

After the successful launch of PSLV C7. From left: C Annamalai, BN Suresh, N Narayanmoorthy, G Madhavan Nair, K Krishnaswamy, A Subramanian and KN Shankara.

GSLV liquid engine strap-on. The vehicle has four strap-ons.

GSLV cryo-engine under testing. The cryo-engine powers the third stage of GSLV.

Integration of GSLV first stage in progress.

Strap-on being attached.

GSLV second stage being lifted at the Mobile Service Tower (MST).

Integration of Cryogenic Upper Stage in the Vehicle Assembly Building (VAB).

Closure of the heat shield completes integration

GSLV all set to lift-off from the first launch pad.

GSLV lift-off from the second launch pad.

After a successful GSLV flight. From left: PS Goel, G Madhavan Nair, S Krishnamurthy, TKA Nair and G Ravindranath.

After the Chandrayaan-1 launch. From left: MKG Nair, MC Dathan, George Koshy, K Radhakrishnan, G Madhavan Nair, TK Alex, M Annadurai and R Navalgund.

Indigenously developed cryo-stage of Russian design. ISRO has mastered this technology.

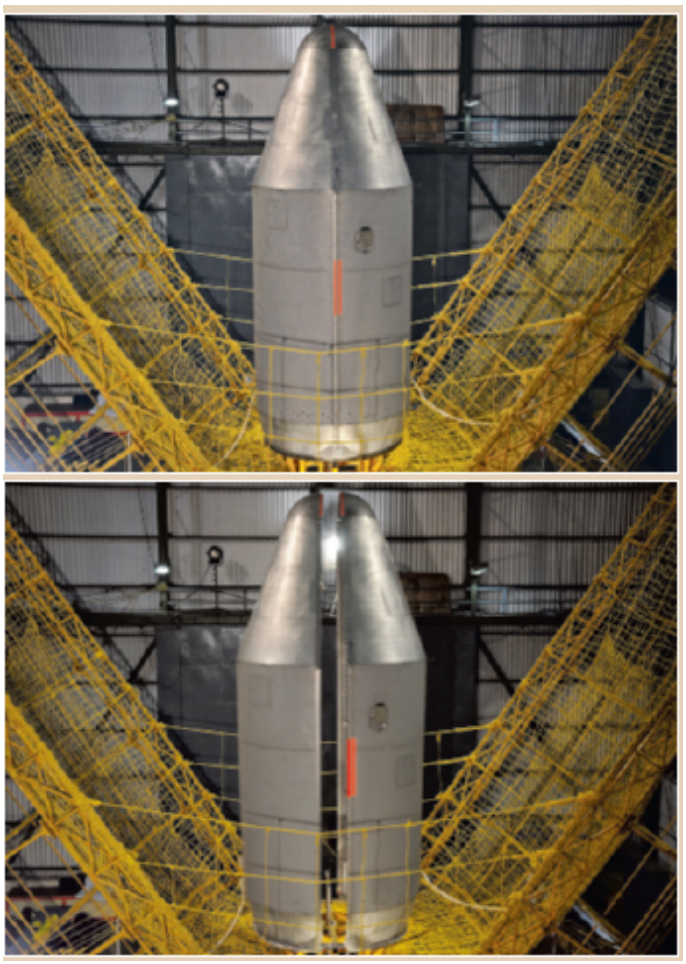
GSLV Mk III first stage has a core of two clustered liquid engines. Picture shows hot testing of the same at ISRO Propulsion Complex at Mahendragiri in Tamil Nadu.

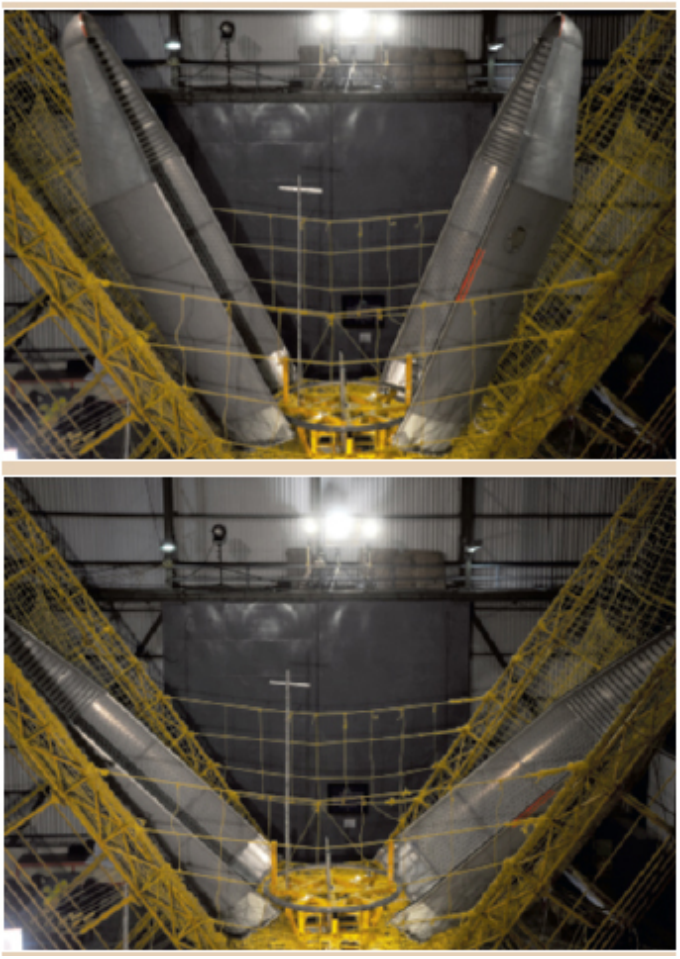
A close-up view of the GSLV Mk III clustered engine hot test.

Indigenously developed cryo-engine (CE 20). Seen from left: V Narayanan, AS Kiran Kumar, S Somanath and Mathew George.

K Sivan with his colleagues at the Actuator-in-Loop Simulation facility. From left: Mohan Rao, Biju Prasad (partly seen), Naryanan Namboothiri, VR Lalithambika, J Jayaprakash, K Sivan, I Sudar and Unnikrishnan Nair.

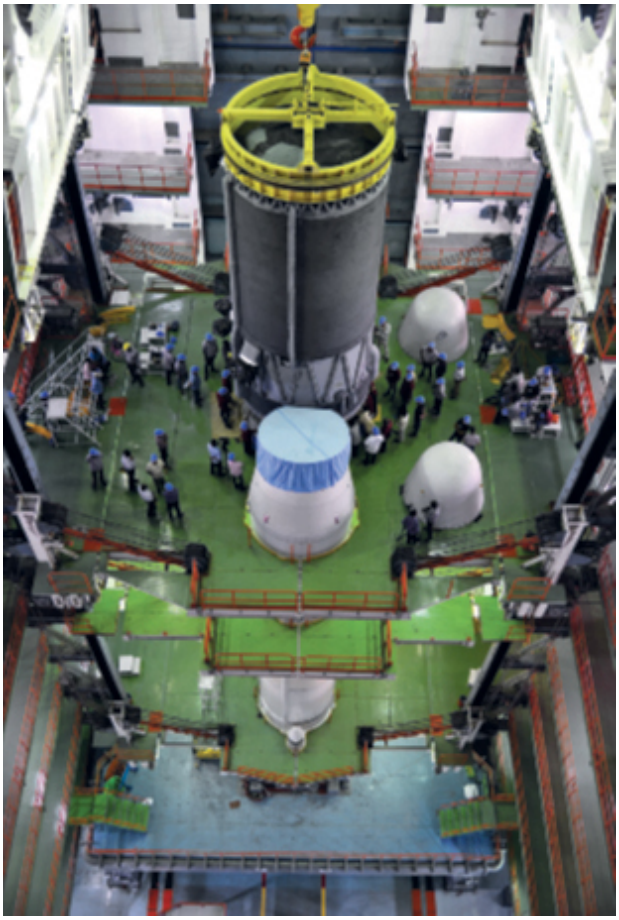
From July 1980 to June 2017, that is, from the first successful launch of SLV-3 to the successful launch of GSLV Mk III, it had been a 37-year- long journey for ISRO, but then each and every year of it was well spent in learning new things, both from successes and from failures. In the days of Sarabhai and Dhawan, the people working in ISRO felt that they were partners in nation building. Evidently that spirit still pervades ISRO.





High-speed camera photographs of the GSLV Mk III heat-shield separation. The whole process of heat-shield separation takes a fraction of a second.

Integration of GSLV Mk III strap-ons.



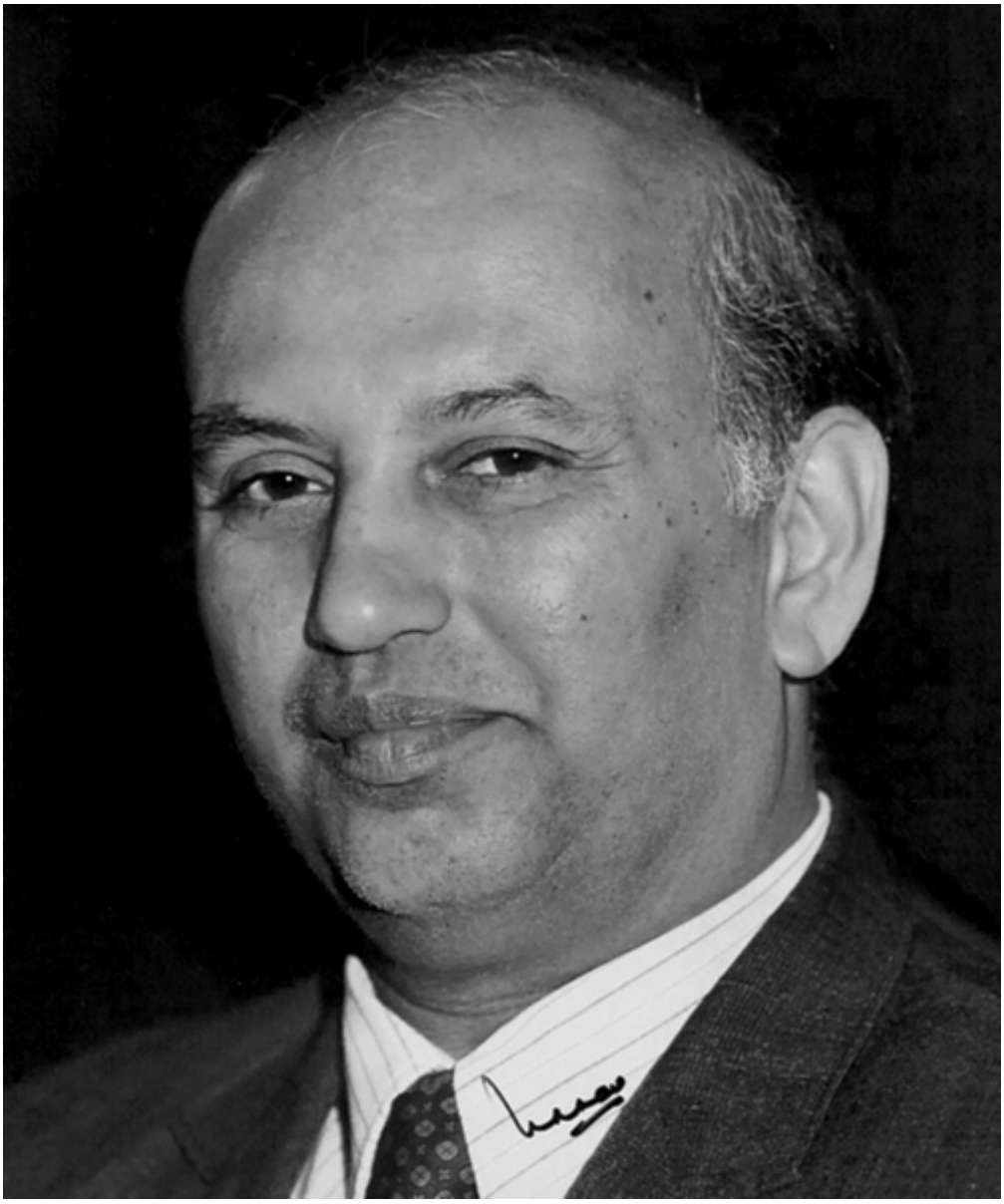
Indigenous cryo-stage being integrated.

A note on failures

No organisation in the world has mastered rocketry without facing failures. And ISRO is no exception. The first flight of the SLV-3, the first two flights of the ASLV, the first flight of the PSLV and the fourth flight of the GSLV had all failed. But every failure has a lesson and the secret of success is to learn that lesson. Benjamin Franklin famously said: “Things that hurt, instruct.” ISRO did learn a lot from all its failures.

★★★

The maiden flight of the GSLV Mk III with an indigenously developed cryo-stage was a success (5 June 2017). It is ISRO's most powerful rocket to date.



UR Rao

Satellites of ISRO

Introduction

If ISRO's rocket technology was born in a church with pigeons for company, its satellite technology was born in empty industrial sheds in Peenya, Bangalore (now Bengaluru). It was under the guidance of UR Rao that India's first satellite, *Aryabhata,* was designed, fabricated, tested and launched – all in 31 months. Later, Rao became Chairman of ISRO.

Here, we do not distinguish between the terms satellite and spacecraft, though the latter is generally used to denote those that operate beyond the Earth's influence; examples are Chandrayaan-1 and Mangalyaan.

For convenience, they can be categorised into four types: communication, remote sensing (or Earth observation), navigation and space science. We do not intend to describe each and every satellite launched by ISRO; rather, we deal below with those historic ones that paved the way for today's constellation and then summarise the current situation.

Aryabhata and Bhaskara I and II

Aryabhata, the scientific satellite, was launched on 19 April 1975 by the Interkosmos rocket of the Soviet Union (now Russia). In spite of its very short mission life, the Dhawan–Rao duo had decided that the very next satellites, *Bhaskara I* and *II,* would be remote sensing satellites. (A remote sensing satellite takes pictures of the Earth in different bands of the electromagnetic spectrum). This was audacious because to perform imaging of the Earth from a spinning satellite (which *Aryabhata* was) called for the deployment of a host of new technologies. Yet, the decision was in tune with Sarabhai's vision of using space technology for national development. *Bhaskara I* and *II* were also launched by the Soviet Union, in 1979 and 1981, respectively. Besides these, two more satellites, named *Rohini,* were launched using ISRO's own SLV-3 between 1979 and 1981.

Satellite bus

A satellite bus is somewhat similar to the unfurnished skeletal structure of a house (or flat). We know where the kitchen is, where the toilets are, and so on. We only need to buy the necessary furniture and position it in the proper locations to make the house operational.

Thus, a modern satellite bus is its skeletal 'infrastructure' that provides locations for all the housekeeping equipment and a specific genre of payload(s). The bus also ensures a benign thermal regime. (Without this provision, temperatures across the satellite may vary greatly). For example, the I-4K bus developed by ISRO provides all the infrastructure for communication satellites weighing 4000–6500 kg. (Here, I stands for INSAT and 4K for 4000 kg).

APPLE

APPLE stands for Ariane Passenger Payload Experiment. Ariane was the name of the launch vehicle that the European Space Agency (ESA) was developing in the 1970s. ESA invited proposals for a free ride on the third developmental flight of Ariane and, from among 72 proposals received from across the world, the one from ISRO was chosen. This in itself was a pat on the back for ISRO but more creditably, APPLE made India master several state-of-the-art technologies associated with space communications, Earth observations and space science – all in 30 months and within a budget of Rs. 21 crore.

On 19 June 1981, the Ariane rocket placed APPLE in an elliptic orbit of 210 km × 36,201 km. The job of moving it from here to the geostationary orbit (circular) at about 36,000 km was carried out by the apogee boost motor, which was the legacy of the fourth-stage motor of SLV-3.

During its lifetime of 27 months, all the communications experiments and demonstrations planned were successfully carried out using APPLE, even though it faced several problems, including non-deployment of a solar panel. Solving these problems and managing a "handicapped" APPLE gave ISRO valuable experience that came in handy while developing operational satellites, both for remote sensing and for communications.

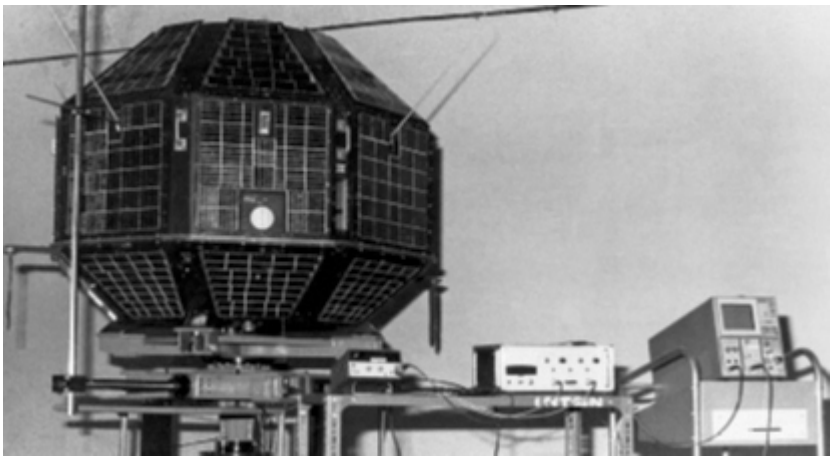
Now, it is time for some historic firsts in operational systems.

INSAT-1 series

Jacques Blamont, who helped India launch its space programme in 1963, recalled: “You have to realise that when I heard Vikram Sarabhai explain his dream…, the first geostationary satellite, Syncom, had not yet been launched.” Yes, Sarabhai’s dream included communication satellites in geostationary orbits and India’s first operational system was named INSAT-1, the acronym standing for Indian National Satellite system. The INSAT-1 series was built by Ford Aerospace Communication Corporation (FACC) in the USA to the specifications laid down by ISRO. The series comprised four satellites: INSAT-1A, 1B, 1C and 1D, launched during the period 1982–1990.

INSAT-1A and 1C were failures and the insurance companies paid compensation to the Department of Space for the total loss of the satellites.

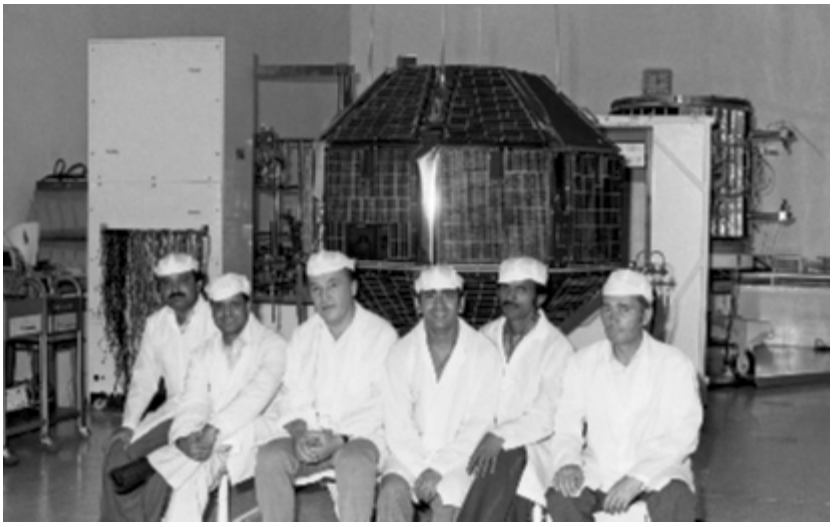
The INSAT-1B and 1D systems served the nation till 2002 in the following areas: TV broadcasting to community TV sets, distribution of TV programmes for rebroadcasting, radio networking, telecommunications, meteorological Earth observations and meteorological data collection from unattended platforms. As quipped by UR Rao, a former Chairman of ISRO, the cloud cover images obtained through INSAT-1 and broadcast on the national TV network every day made every person in India a meteorologist!



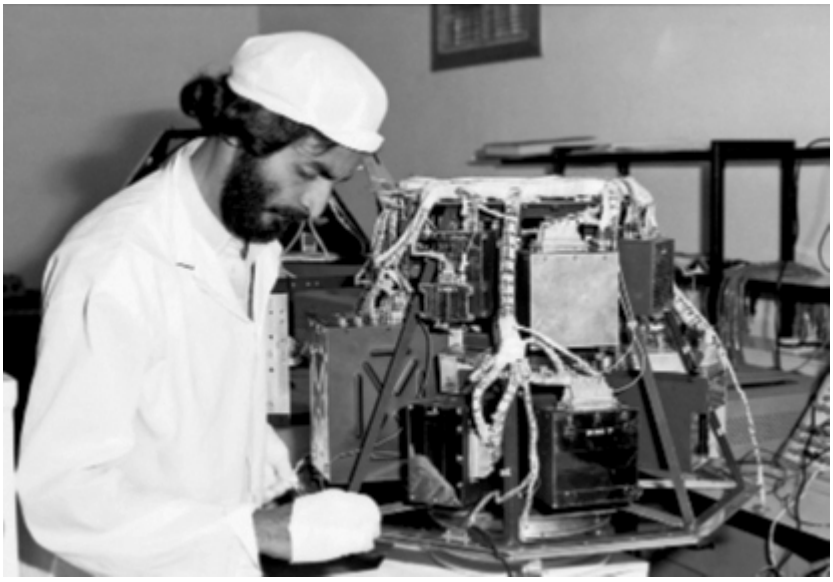
Aryabhata, India’s first satellite, at the Peenya industrial sheds of Bangalore. It was launched free of cost by the Soviet Union (now Russia) on

19 April 1975.

Photograph taken moments before the first signal was received from Aryabhata at Bear Lake, USSR.

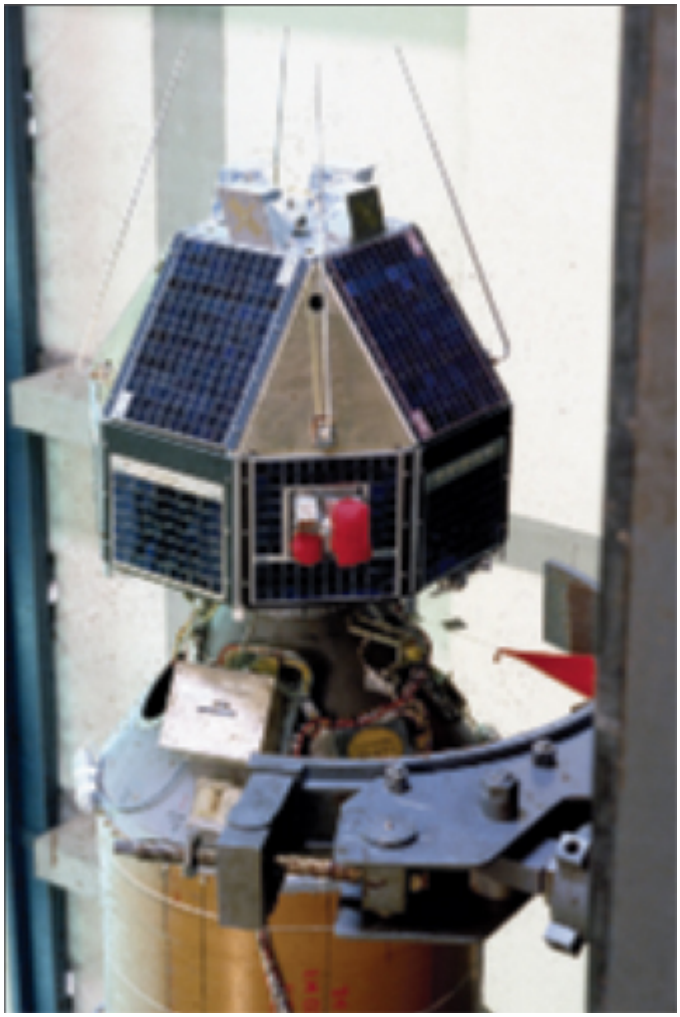


The Bhaskara team in the USSR. From left: VR Katti, K Kasturirangan, Anatoly M Poppel, Arun Batra, George Joseph and (not identified).



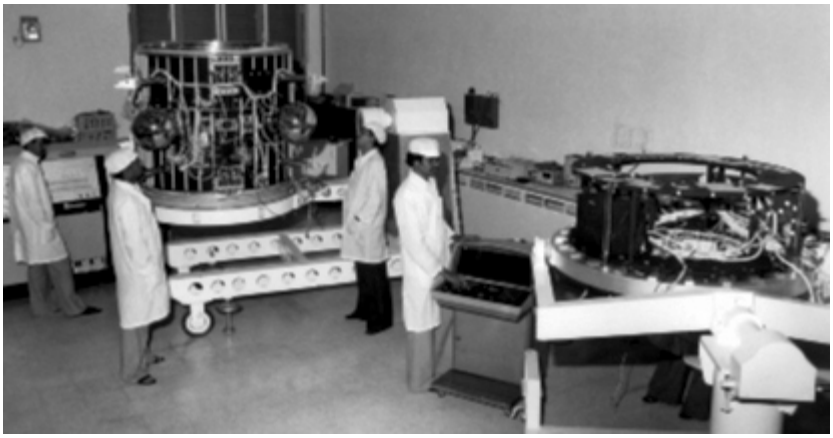
The Rohini satellite being assembled at Peenya. This satellite was flown on SLV-3.

Satish Dhawan (closed fists) and UR Rao (extreme right) looking at the model of the ISAC building. Context: Bhoomi puja day for the new building.



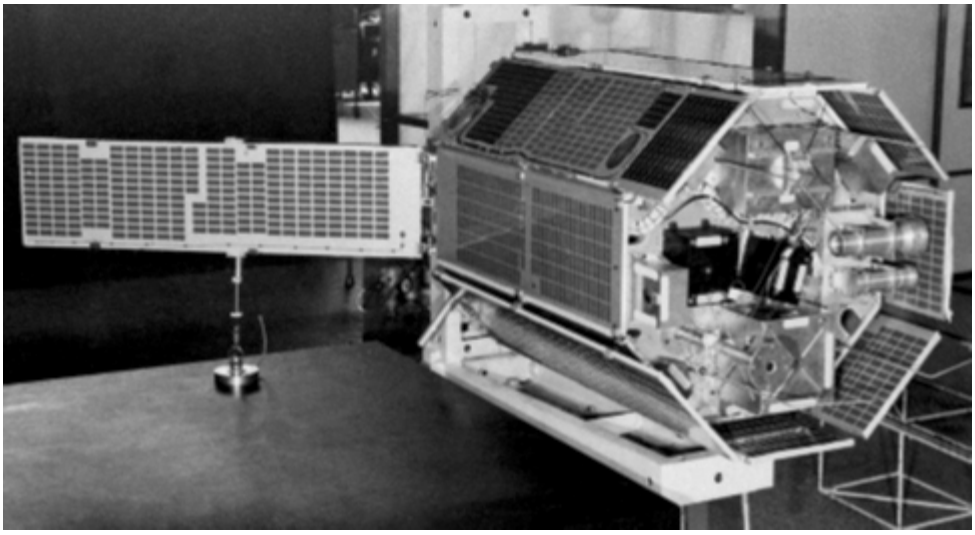
The Rohini satellite assembled on the fourth stage of SLV-3.

The APPLE satellite undergoing centre-of-gravity and moment-of-inertia testing.



The integration team of the APPLE flight model at Peenya. From left: Gopalakrishnan, KSV Seshadri, Pattabhiraman and Anil Rao.

The APPLE satellite being loaded into an aircraft for transportation to the Toulouse Facility, France.

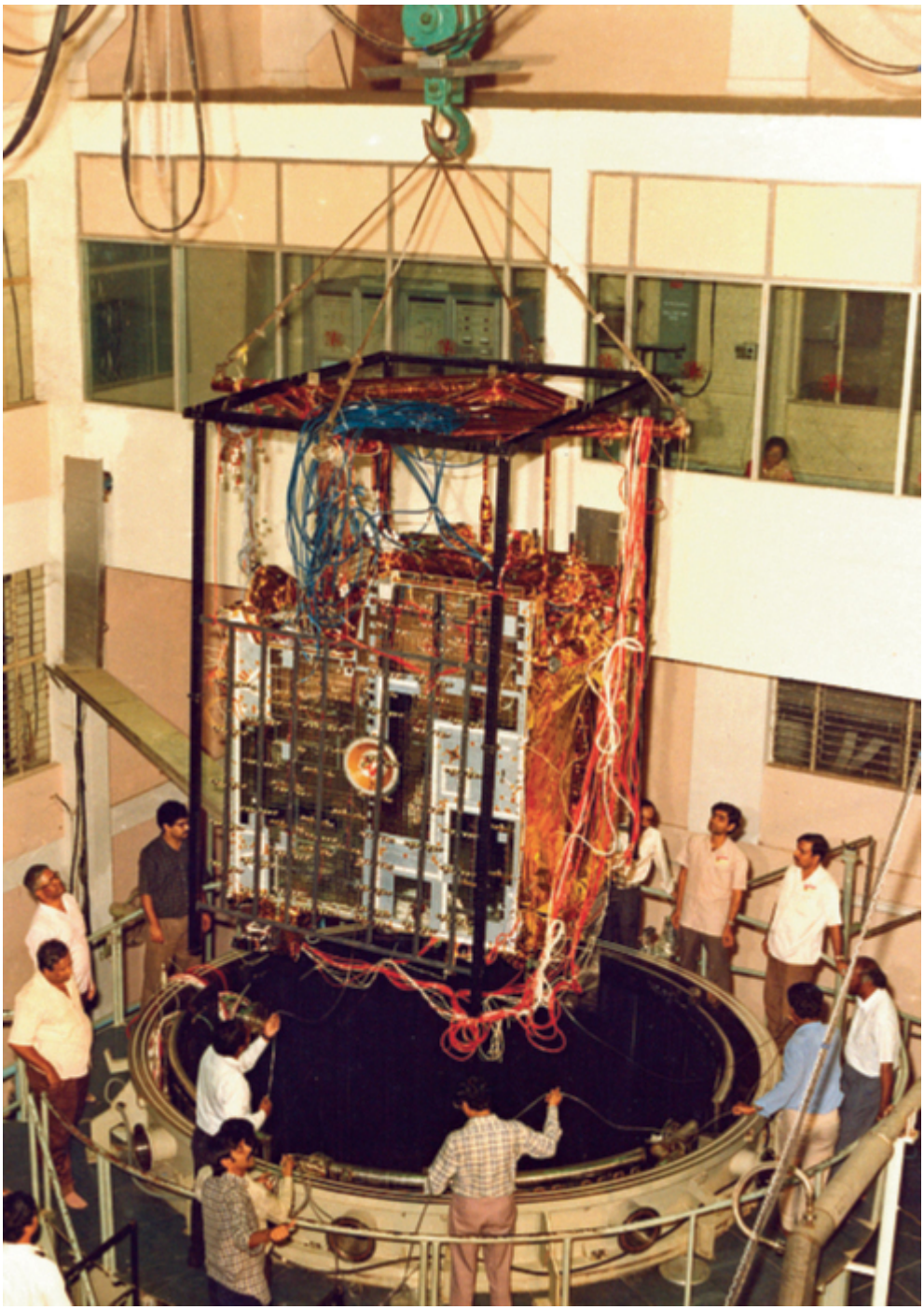


The SROSS satellite under solar panel deployment testing. This was *orbited by ASLV.*

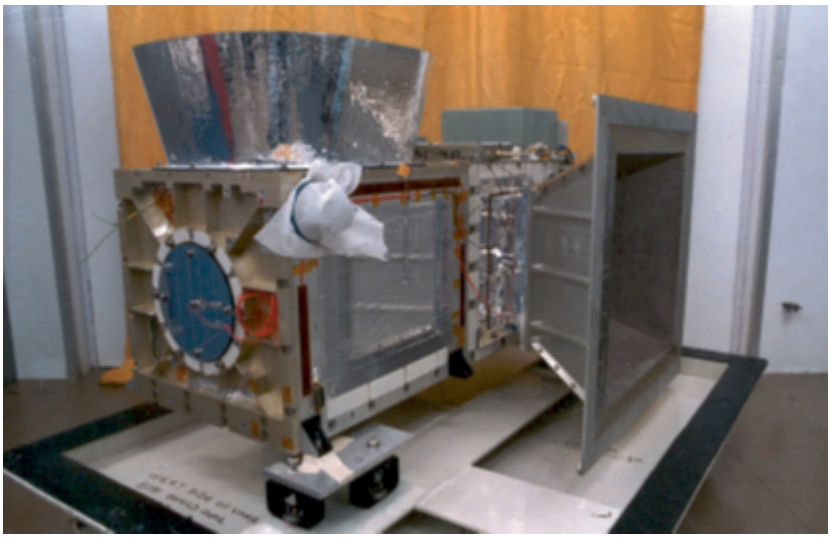
UR Rao (extreme right) with Indian cosmonauts Rakesh Sharma and Ravish Malhotra.

The INSAT-1 team at Ford Aerospace: Front row (from left): Gopal Rao of IMD (in suit), (not identified), SB *Iyer (folded hands), JP Singh, Denis Killen of FACC (in suit), UR Rao (with name badge), PP Kale (dark hair), (not identified), S Krishnamurthy of Doordarshan (brown suit), K Kasturirangan (hand in pocket), Thiagarajan (bearded), K Narayanan, KPM Bhat (extreme right). Behind (from left): P Damodaran (folded hands), M Nagarajan (behind Damodaran), SN Patnaik (INSAT SSPO), George Thomas (brown sweater), Anantharam, Brian Saleh of FACC (in suit), Rawal (of DoT), (not identified), P Ramachandran (between UR Rao*

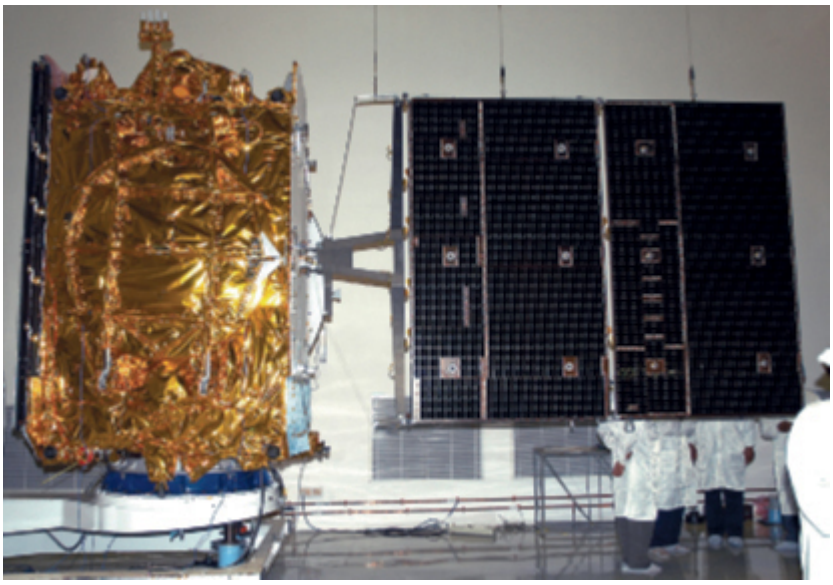
and Kale), TK Alex (behind Kale), George Joseph (close to left shoulder of Kale), (not identified), Valiappan (behind Joseph), (not identified), VK Kaila (spectacles), NK Malik, (not identified), (not identified), PS Goel (between Krishnamurthy and Kasturirangan), Dipti Rastogi (behind Goel), Ponappan (thick hair), (not identified), (not identified) and RM Vasagam.



The INSAT-2C satellite being loaded into the Thermovac Chamber at ISAC.



Very-high-resolution radiometer for INSAT-2, used to take pictures of cloud cover.

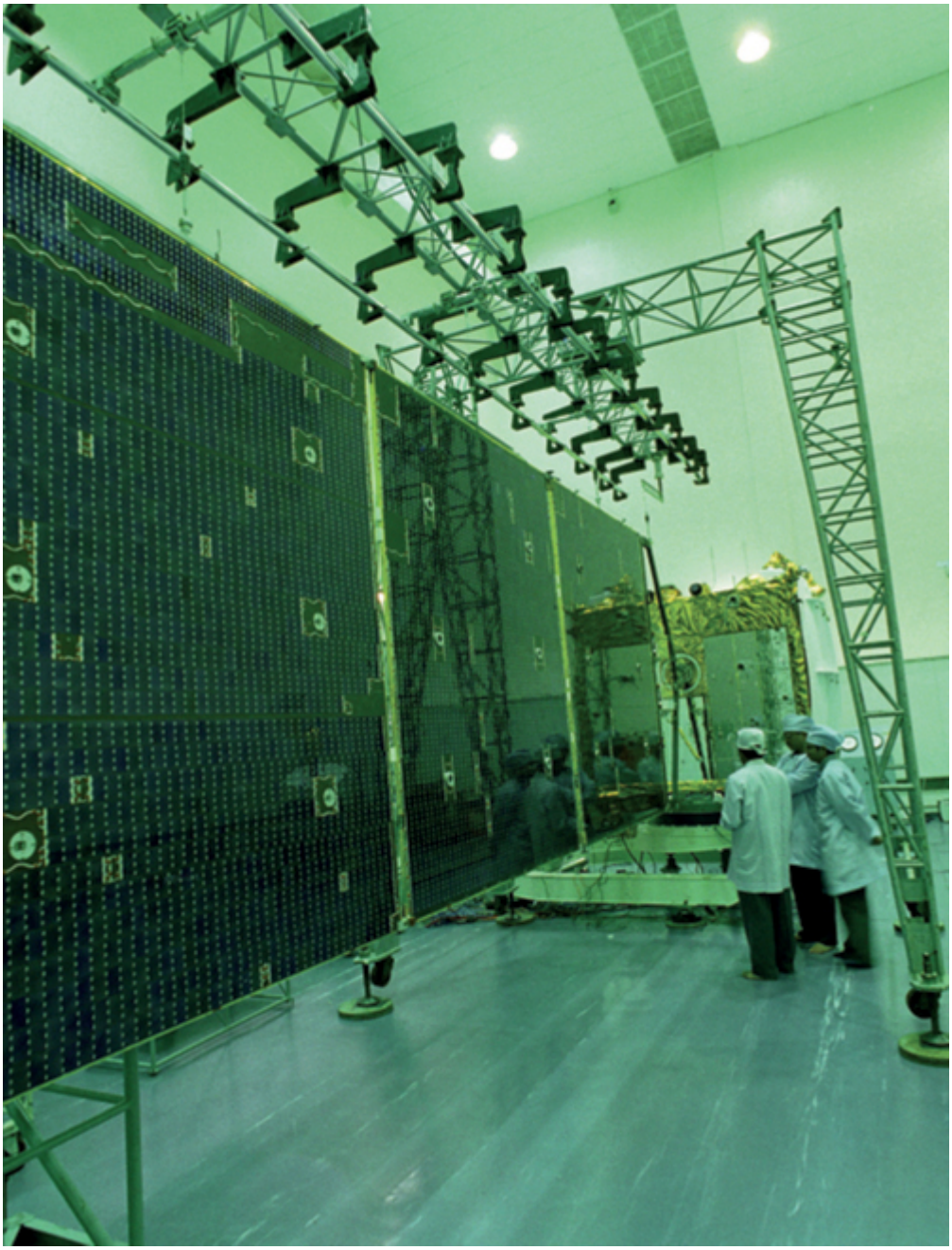


INSAT-4C with deployed solar panel under testing. Unfortunately, the launch vehicle failed to orbit the satellite.

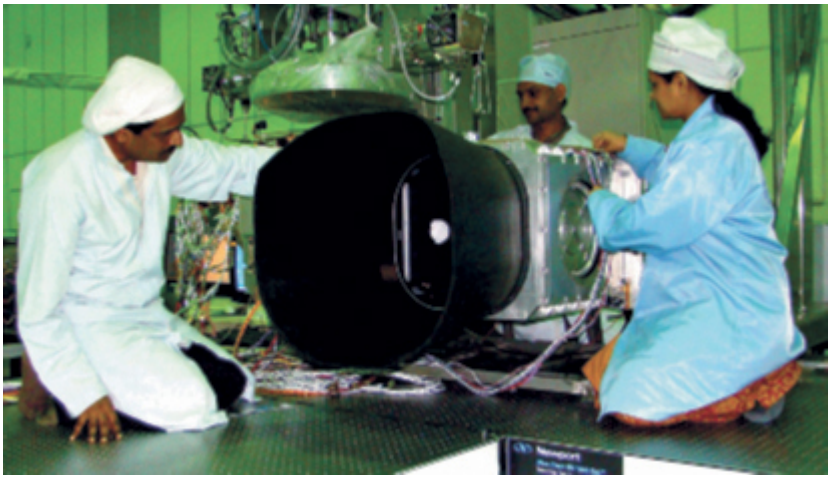
INSAT-4CR before heat-shield closure of the rocket. Launched by GSLV in 2007, it provided DTH services, video picture transmission, digital satellite news gathering, and so on.

Assembling the reaction wheels in a super clean room in IISU. These are used to change the attitude (that is, orientation in space) of satellites.

Foreign customers of ISRO working on their satellites.

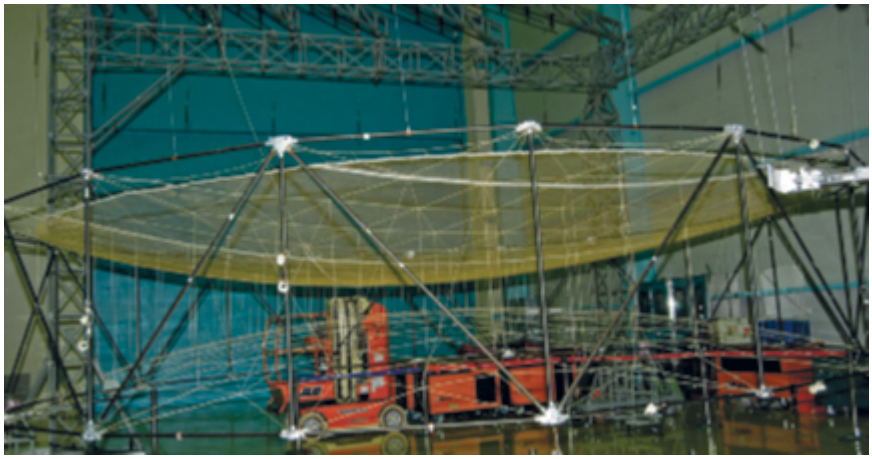


INSAT-3D sounder payload is a newly developed 19-channel sounder. From left: Amitvikram Kurulkar, Manoj Kumar and Barkha Gupta.



GSAT-1 solar panel deployment testing. Launched on-board GSLV-D1 in 2001, this satellite was used to conduct experiments in digital audio broadcasting, internet services and compressed digital transmissions.

People working on the first high-power Ku-band payload panel used on INSAT-4A. From left: MC Gajjar, MC Trivedi, Geeta D Mamtora and Monil Patel.



Unfurlable antenna deployment testing of GSAT-6.

IRS-1 A

With the hands-on experience gained through *Aryabhata, Bhaskara I* and *II,* APPLE and the INSAT-1 series, it was natural for ISRO to attempt to create its own fully operational satellite. The first in this category was IRS-1A, the acronym standing for Indian Remote Sensing Satellites, The IRS-1 system was designed to take different types of remote sensing payloads, incorporating all the features of a modern satellite such as precise orbit control, high data rates, on-board storage, thermal isolation, and so on. Complementing the satellite in space was the elaborate ground system for data reception, processing and disseminating the same in a format suitable to the users.

Designers of space systems are in general conservative, and thus, tend use components and systems with proven heritage. But in the case of IRS-1, ISRO took the bold decision to use electronic scanning for imaging using the then newly introduced charge-coupled devices (CCDs) in place of the conventional mechanical scanners. This decision resulted in "a more compact payload configuration with high figure of merit index."

There were three satellites in this series: IRS-1A, 1B and 1C, all of which were launched by Russia on commercial terms. As pointed out by PS Goel, "the IRS-1 proved to be a robust and reliable spacecraft bus and was subsequently used for a series of satellites launched by PSLV

developmental flights as well as for taking various kinds of payloads like Ocean Colour Monitor, scanning radiometer, etc.”

INSAT-2A

What IRS-1A was to remote sensing, INSAT-2A was to the communication systems of ISRO. It was the first indigenously developed operational communication satellite of ISRO (to start with, it was not meant to be operational!). Communication satellites are generally launched into geostationary orbits at an altitude of around 36,000 km. The experience gained through APPLE and the INSAT-1 series, including the failures faced, was utilised in the design of INSAT-2A.

INSAT-2A was launched on 9 July 1992 (10 July in India) from Kourou in French Guiana by the European Space Agency (ESA) using their Ariane rocket. This timely launch saved ISRO from a potential embarrassment! This was because INSAT-1C (bought from FACC) had failed and to assure continuity of telecom and TV services to the nation, ISRO had to lease some transponders from *Arabsat.* Just a few days before the lease period was to end, INSAT-2A was pressed into service, saving ISRO its blushes!

Remarkably, the successor to INSAT-2A, namely INSAT-2B, was launched the very next year on 22 July 1993 (23 July in India).

To quote P Ramachandran, the Project Director of the INSAT-2 system: “Considering the fact that the least cost for twelve *Arabsat* transponders was $10 million a year, the thirty-six transponders on the two satellites (INSAT-A and 2B) would have saved about $210 million (Rs. 630 crore in 1995), about three times the project cost of Rs. 200 crore, not to mention the broadcast and meteorological payloads and the infrastructure that was created.”

Something special

When we say that there are over 40 satellites of ISRO in orbit today, one may think that building satellites is routine stuff. Not true. We take one

example: the satellite named TES (Technology Experiment Satellite) launched by PSLV in 2001.

It was mid-1999 when India was facing the Kargil war and ISRO felt it ought to do something for our soldiers. To quote PS Goel: "… to achieve a 1-meter resolution from an existing 5.8 meter (resolution) panchromatic camera.… To develop as many as eleven new technologies; to configure a new satellite altogether; to build subsystems around the new payload; to introduce concepts like step and stare and phased array antenna to dump the data to the designated ground station – to do all this in two years seems impossible! … But the motivation was different. We all felt that if we could save the life of even a single soldier… with our efforts, we would have achieved the mission of our lives…. Some of the women employees of ISRO sent their children to their mothers' place so that they could devote more time to the mission. Some others shifted their houses closer to the lab so that they could attend to late-hour duties.… And the satellite was launched on 22 October 2001 within twenty-four months of the go-ahead!". And it was a success.

Doing space science with satellites

The very first satellite, *Aryabhata,* was a scientific satellite. There were scientific payloads on-board the satellites launched by the ASLV. Similarly, a scientific payload designed by the Tata Institute for Fundamental Research (TIFR) for studying X-rays from stars rode piggyback on the IRS-P3 satellite launched by PSLV in 1996. But the most spectacular scientific missions of ISRO were Chandrayaan-1 and the Mars Orbiter Mission (MOM). And in 2015, ISRO launched ASTROSAT dedicated to studying celestial sources in the X-ray, optical and ultraviolet spectral bands. We describe these briefly below.

Chandrayaan-1

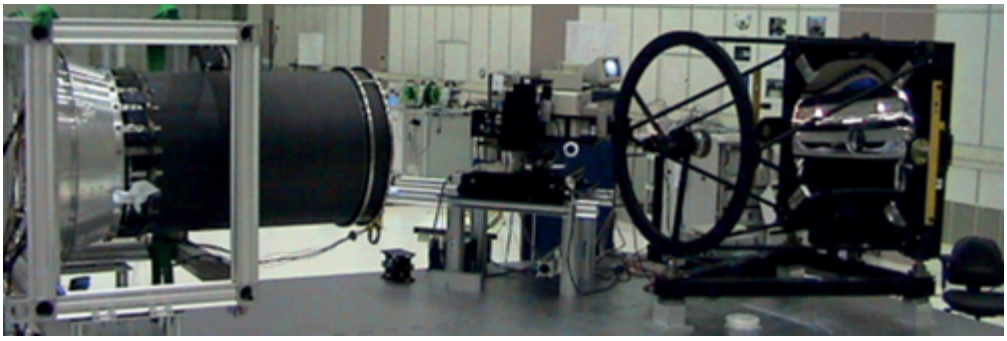
With the successful launch of GSLV-D1 in 2001, ISRO could justifiably claim to have achieved all the goals set for it by the visionary Vikram Sarabhai in his famed Decade Profile released in 1970. Sarabhai laid

emphasis on carrying out missions of practical benefit to people. Now it was time for ISRO to seek new avenues and look beyond our planet Earth. Also, it was essential to engage the talented pool of scientists and engineers with new challenges. The result was Chandrayaan-1, ISRO's first Moon shot. It took over four years for ISRO to convince itself, the scientific community and the Government to take the mission.

In the glare of media publicity that followed the discovery of water on the Moon by Chandrayaan-1, some of the significant features of the project and the mission were eclipsed. For example, the Chandrayaan-1 mission saw unprecedented international participation: the USA, Germany, Bulgaria, Sweden, Japan and the UK. The project team which built the spacecraft was under pressure to include last-minute increases in payload mass and yet deliver the spacecraft on time. Normally, a project of this nature would call for at least three models: the proof-of-concept model, engineering model and flight model. In the case of Chandrayaan-1, however, there was only one model, namely, the flight model! M Annadurai, the project director, recalled: "Sceptical eyebrows were up among the international partners. But after the MIP (Moon Impact Probe) impacted on the lunar surface on 14 November 2008 and after the first signatures of water presence were received and data from all the science instruments started flowing, all scepticism vanished. And the international partners echoed us, saying "this is the Indian way of doing things!"

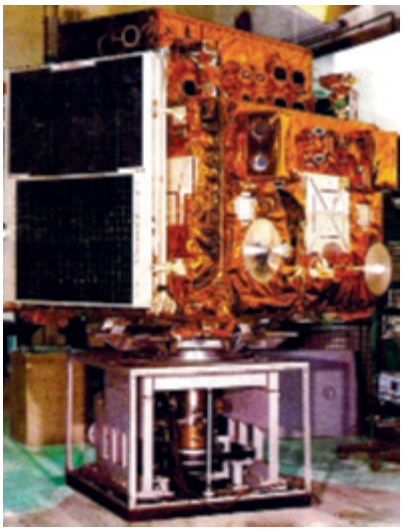
Chandrayaan-1 and the PSLV that launched it became household names.

GSAT-10 in the Compact Antenna Test Facility. Launched in 2012, this had on-board 30 communication transponders, besides a navigation payload known as GAGAN (GPS-aided GEO Augmented Navigation). It also carried a Ku-band beam to help ground antennae point accurately towards the satellite.

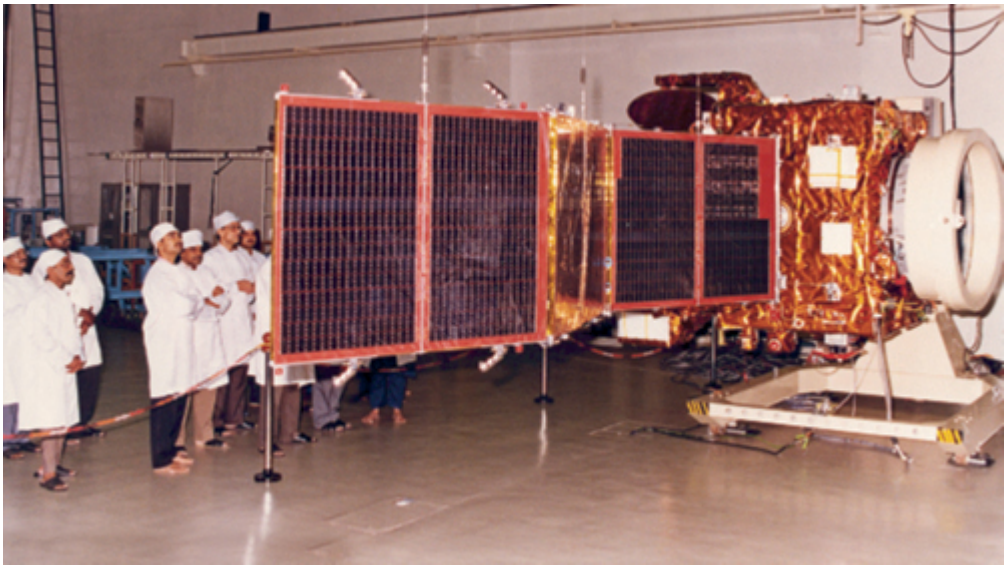


The CARTOSAT-1 payload, which has a panchromatic camera that provides stereo imaging with a geometric resolution of 2.5 m.

Solar panel deployment testing of the CARTOSAT-2 series spacecraft. Applications of these satellites include: cartography, coastal land use, utility management such as road network monitoring and water distribution.



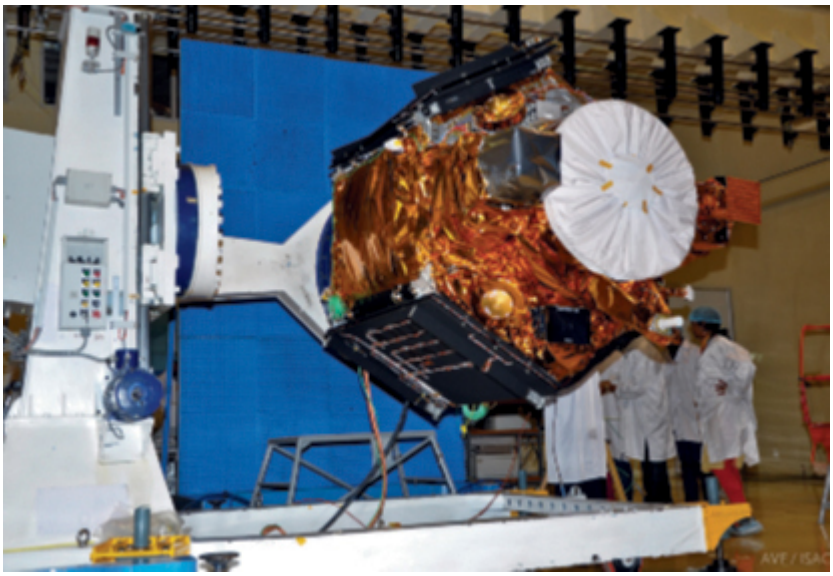
IRS-1A, India's first operational remote sensing satellite, undergoing dynamic balancing testing. This was launched by the Soviet Union (now Russia) in 1988.



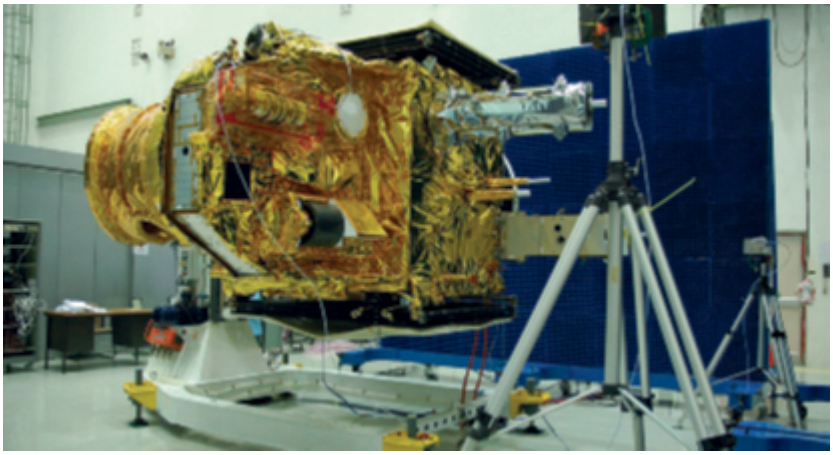
IRS-P4 solar panel deployment testing. This remote sensing satellite was launched, along with a German and a Korean satellite, by PSLV in 1999. It is no longer in operation.

People working on SCATSAT in a clean room.

RESOURCESAT-1 under preparation for solar panel deployment. Launched in 2003 by PSLV, this is no longer in service.



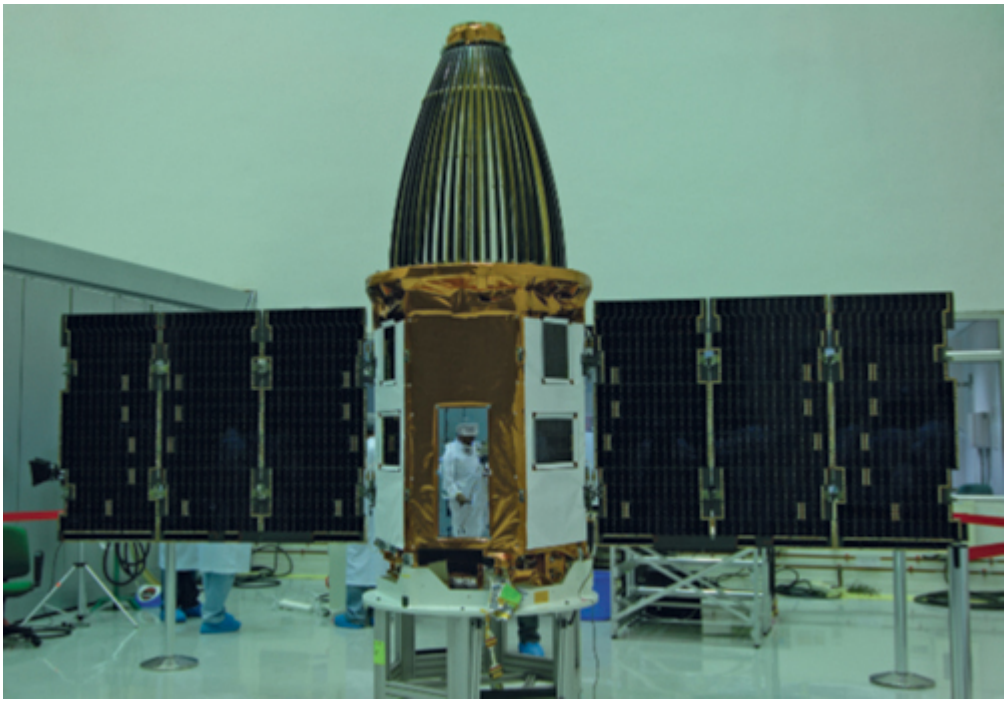
CARTOSAT-2 under preparation for EMI/EMC (electromagnetic interference/electromagnetic compatibility) testing.



Indo-French satellite Megha-Tropiques under testing. This was used to study the water cycle and energy exchanges in the lower part of the atmosphere, known as the troposphere.

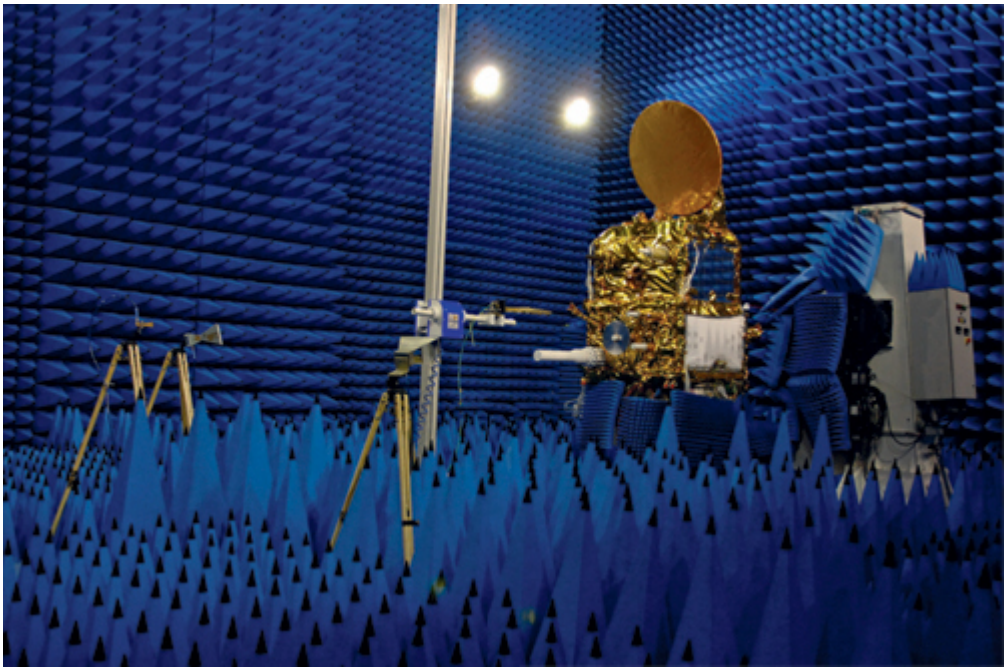
Radar Imaging Satellite (RISAT) is a multimode (fine resolution, spotlight, medium resolution and coarse resolution) spaceborne C-band Synthetic Aperture Radar (SAR), which was launched in April 2012. Selection of frequency and polarisation was based on applications. The objective of this satellite was applications conforming to national civilian requirements such as Agriculture, Soil Moisture, Forestry, Flood Mapping, Ocean-related Studies, etc. The technology used is state-of-the-art and can survive obsolescence and is adaptable for other frequency bands in future missions.

Picture shows (from left): Rakesh Bhan, RB Singh, DB Dave, Vivek Singh, Tapan Misra, KC Bhagat and Binit Roy working on the RISAT payload.

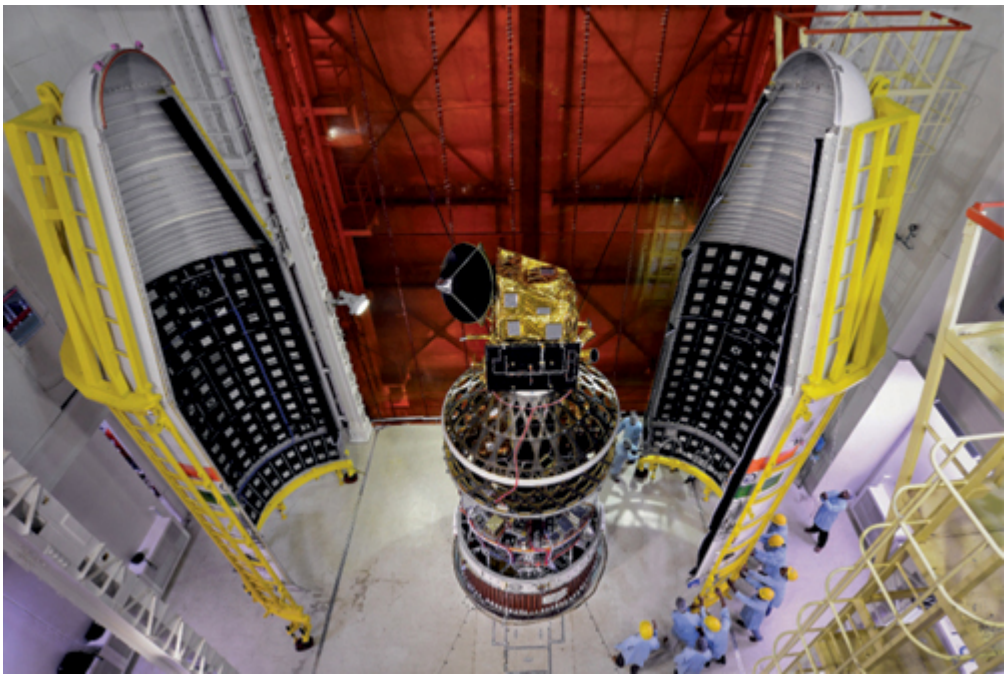


RISAT-2 under solar panel deployment testing. Launched in 2009, this has all-weather capability (it could take pictures of the Earth's surface even in cloudy conditions).

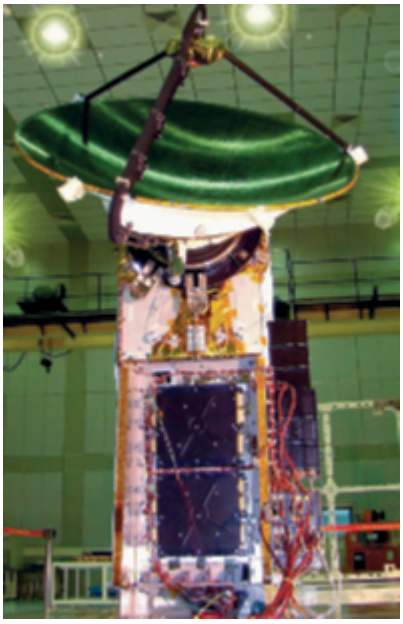
French remote sensing satellite, SPOT-6, being integrated with the PSLV. The satellite is on top of the fourth stage of PSLV.



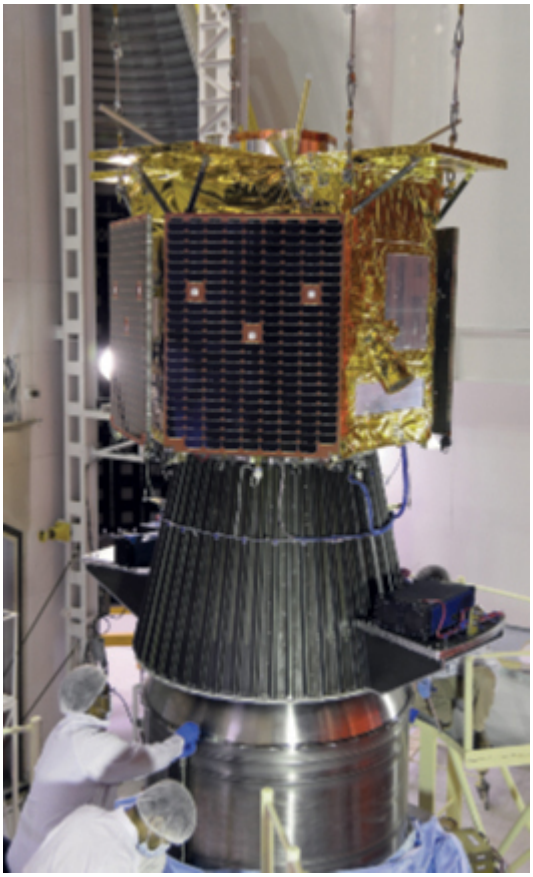
The SARAL satellite undergoing EMI (electromagnetic interference) testing. SARAL was an Indo-French joint mission for studying oceans.



SCATSAT integrated with PSLV. It carried an instrument called the scatterometer (see above), which provides information on winds useful in weather forecasting, cyclone detection and tracking.

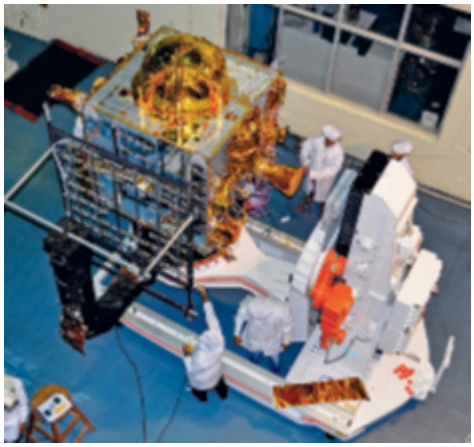


Italian satellite, Agile (left), and Singapore satellite, TeLOS, both launched on-board the PSLV.



The DMC satellites of the United Kingdom being prepared for launch by the PSLV.

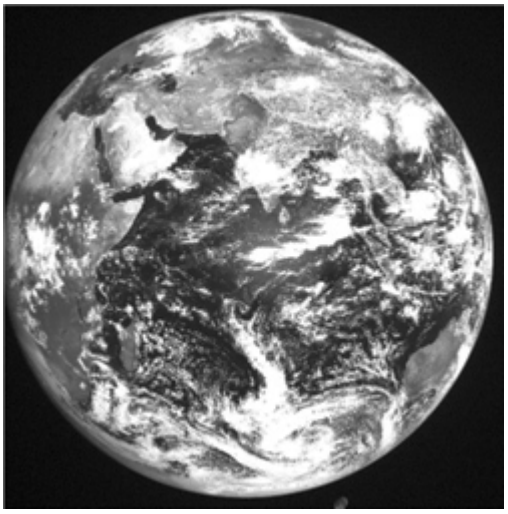
IRNSS-1A (Indian Regional Navigation Satellite System) under centre-of gravity and moment-of-inertia testing in a clean room. This system comprises seven satellites.



IRNSS-1G under testing. Now, all seven satellites are in place.

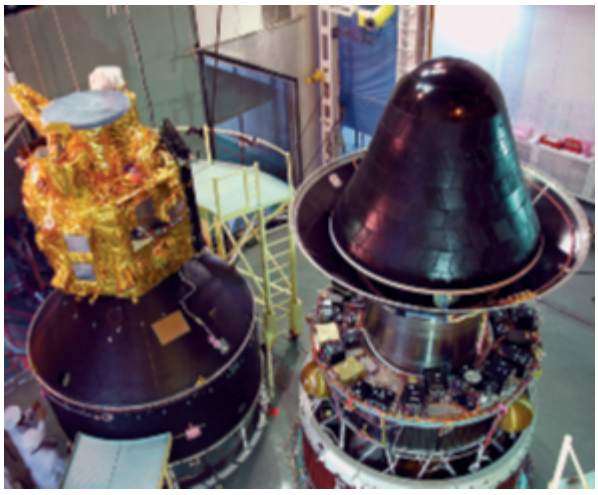
GSAT-11, India's heaviest communication satellite (5854 kg), was successfully launched on 5 December 2018 from Kourou launch base, French Guiana, by Ariane-5 VA-246.

INSAT-3D electronic package integration and testing on the Integration deck. From left: Durairaj, Ranjan Parnami and Anish Saxena.



First image of Earth taken by INSAT-3DR.

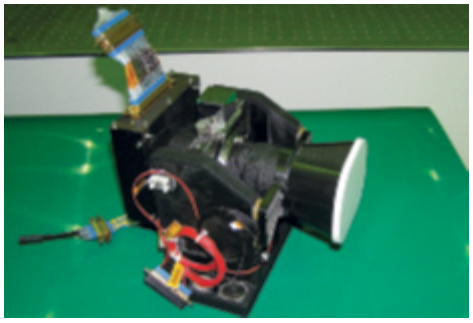
For the first time, ISRO recovered an orbiting satellite in 2007. This was known as the Satellite Capsule Recovery Experiment-1(SRE-1). Picture shows the satellite being prepared for launch.



SRE-1 integrated with the vehicle. CARTOSAT-1, which was also launched with SRE-1, is seen on the left.

Satellite Capsule Recovery Experiment (SRE) in the process of recovery.

Chandrayaan-1.



Chandrayaan-1 payload, Hyper Spectral Imager.

Mars Orbiter Mission (MOM): Mangalyaan

On 24 September 2014 at 07:27 IST, ISRO's spacecraft, MOM, entered the Martian orbit, creating history and drawing the attention of the entire world. India became the first nation to have achieved this in its very first attempt. Even in January 2018, MOM was sending pictures of Mars. One can visit the ISRO website (www.isro.gov.in), navigate to Missions and download the Atlas of Mars pictures sent by MOM.

No other mission of ISRO's received the media attention that MOM did. Here, we attempt a popular summary.

MOM is like shooting from a moving platform (Earth moving at 107,000 kmph around the Sun) at a moving target (Mars travelling around the Sun at 86, 870 kmph) and hitting the bull's eye. Adding to the complexity of the mission is the continuously varying distance between the two planets. What makes the mission theoretically possible is the precise knowledge of the motion of the planets around the Sun. The engineering feat lies in making MOM follow precisely the computed path throughout its 300-day journey. This meant that the rocket that launched MOM (PSLV), the various housekeeping equipment on-board, the ground-based telemetry and tracking and command systems, the various software packages, and so on, all worked to near perfection. In other words, the success of MOM is a testimony to the professionalism of the scientific and technical personnel of ISRO.

Currently operational satellites of ISRO

A. Communication satellite system

The Indian National Satellite (INSAT) system today is one of the largest domestic communication satellite systems in the Asia-Pacific region. The key payloads on-board these satellites are the transponders which receive signals from a ground station and amplify and broadcast them across the whole country. The INSAT family as whole now has over 200 transponders in operation, providing services in telecommunications, television broadcasting, satellite news gathering, weather forecasting, disaster warning and search and rescue operations, etc. This number may seem large, but it does not meet the demand at all, which means ISRO has yet to catch up by launching more communication satellites. Some of these carry equipment to take pictures of cloud formations which help predict the weather and track cyclones. Meteorologists use this information to issue warnings about where cyclones are likely to make landfall and what the wind speeds are likely to be.

B. Earth observation satellite system

In the area of Earth observation (that is, remote sensing), ISRO operates a constellation of 17 satellites of which 13 are in the sun-synchronous and 4 in the geostationary orbit. The key payloads on these satellites are the imaging systems which have, over the years, improved significantly. For example, the images taken by IRS-1A in 1988 had a resolution of 36 m, whereas today, ISRO's remote sensing satellites provide images with a resolution of a fraction of a metre. (Spatial resolution refers to the smallest detail one can see in an image). Varieties of instruments have been flown on-board these satellites to provide information in a range of spatial, spectral and temporal resolutions; such images have a wide range of applications, as described elsewhere.

C. Navigation satellites

To navigate simply means to find your way. Satellite navigation is a system that uses signals from a number of orbiting satellites and ground information to determine one's position (longitude, latitude, altitude and time) and subsequent course of movement with a specified level of accuracy. A very commonly used navigation system is GPS (Global Positioning System) of the USA, which was launched in 1995. The Russian counterpart is GLONASS (Global Navigation Satellite System).

ISRO has designed a regional (not a global) system known as the Indian Regional Navigational Satellite System (IRNSS), comprising seven satellites in geosynchronous (that is, 24-hour) orbits, with three of them in geostationary orbits (that is, in the equatorial plane) and four of them in orbits inclined to the equator. All these orbits are at altitudes of about 36,000 km. The system covers the whole of India plus a region extending to about 1500 km around the country. These satellites are built around the I-1K bus. All seven satellites and corresponding ground systems are now operational.

It must be emphasised that GPS, though used routinely by car drivers, is a very complex technology. So is IRNSS. For example, atomic clocks of unbelievable stability are used. An atomic clock may lose or gain one second in 30 million years! In addition, corrections derived from Einstein's

Theory of Relativity are applied to arrive at the correct information. And then you need a large number of satellites.

D. A niche for small satellites

While satellites in general tend to become bigger and heavier, there is a special niche for smaller ones, including nano-satellites of a few kilogram mass.

These carry the so-called stand-alone payloads for Earth imaging and science missions. ISRO has developed two types of buses for this purpose: IMS-1 and IMS-2 (IMS stands for Indian Mini Satellite).

The IMS-1 bus is a versatile bus for the 100-kg class of satellites, with a payload mass of around 30-kg. The first mission of the IMS-1 series was launched successfully on 28 April 2008 as a co-passenger with CARTOSAT-2A. YouthSat, the second mission in this series, was launched along with RESOURCESAT-2 on 20 April 2011.

IMS-2 is a standard bus for the 400-kg class of satellites, with a payload capability of around 200-kg. The first mission of IMS-2 was SARAL, which was the result of cooperation between ISRO and Centre National d'Etudes Spatiales (CNES) of France. SARAL had payloads from CNES on the spacecraft bus developed by ISRO. SARAL was launched on 25 February 2013.

★★★

Mars Orbiter spacecraft mounted on top of the PSLV, just before heat-shield closure.

Mars Exospheric Neutral Composition Analyser (MENCA).

People working on the ASTROSAT spacecraft in a clean room.

Integration of ASTROSAT in progress.

Brahm Prakash

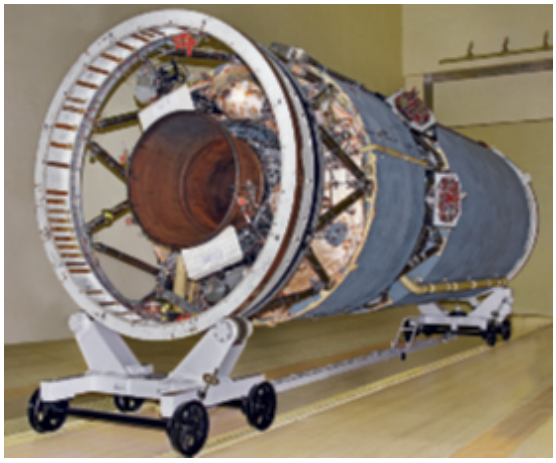
ISRO and Industry

Searching for industrial partners

It was Satish Dhawan who foresaw the need for the national space programme to be backed by the indigenous industry. In the early 1970s, he sent a team headed by APJ Abdul Kalam, the Project Director of SLV-3 in the Vikram Sarabhai Space Centre (VSSC), in search of industries that could support the development and fabrication of the SLV-3. This search ultimately succeeded in enlisting the support of 57 industries, some of which turned out to be long-term partners of ISRO. Examples are: Hindustan Aeronautics Limited (HAL), Larson & Toubro (L&T) and Walchandnagar Industries Ltd. (WIL).

The Vikas engine was manufactured for the first time at MTAR, Hyderabad. Seen in the picture are Kashiviswanathan (fourth from left), AE Muthunaygam (dark suit) and UR Rao (grey suit). The Vikas engine powers the second stage of the PSLV. The GSLV has five Vikas engines powering it.

At Mishra Dhatu Nigam Ltd. (MIDHANI) Materials Museum, Hyderabad. From left: M Narayana Rao (CMD, MIDHANI), MC Dathan and Koshy M George (red shirt).



Indigenised version of the cryo-engine of Russian design, manufactured by MTAR, Hyderabad; Godrej, Mumbai; HAL, Bangalore and LTE, Coimbatore.

The contributions of the industrial associates were diverse – they developed the complex tooling necessary for the manufacture of rocket hardware; they adapted processes such as rolling, welding, heat treatment and precision

machining techniques to meet the stringent performance specifications. The teams could arrive at feasible and mutually acceptable sets of requirements and practices which balanced the performance needs and limitations on resources. The documentation needed was very clearly laid out. The acceptance and rejection criteria for the hardware were very carefully debated and evolved. This type of handholding approach had become more or less a standard pattern in subsequent ISRO – Industry relationships – and a hallmark of its success.

Around the same time, the satellite development activity originally resident at VSSC was shifted to Bangalore, mainly because of its proximity to industrial and other institutional infrastructure that could support environment testing, fabrication of high reliability electronic equipment and light alloy components required for the pioneering satellite development project. Industrial support was also needed for building facilities such as thermo vacuum chambers and clean rooms. Public-sector enterprises such as Hindustan Aeronautics Limited (HAL), Bharat Electronics (BEL), Government Tool Room and Training Centre, the Central Machine Tool Institute (CMTI) and a few private enterprises came forward to support the satellite programme.

There was a need for several thousand low-cost direct reception systems for the historic Satellite Instructional Television Experiment (SITE) Project, undertaken around this time by the Space Applications Centre (SAC) in Ahmedabad, and this was successfully met through industrial collaboration.

On another front, the development of facilities at the newly built launch range at Sriharikota (now known as the Satish Dhawan Space Centre, SDSC) was another major challenge that demanded specialised civil engineering as well as safety engineering skills. SDSC set a new trend for promoting a consortia approach by industry to meet those requirements.

Technology transfer policy

Around the mid-70s, ISRO took steps to promote technology transfer from its R&D Centres to industry by forming the ISRO Technology Transfer Group, with experts from the Centres as members. Directly involving

developmental teams to interface with industry was one of the success factors in the know-how transfer and in overcoming the problems of absorption of technology. The technology transfer items covered a diverse range: rocket propellants, chemical powders that extinguished metal and oil fires, adhesives, precision optical processes, a variety of satellite communications equipment, weather radars and other user-oriented terminals, to mention a few. For chemicals and propellants, industries such as Andhra Sugars and Hindustan Organic Chemicals (or the then NOCIL Ltd.) were chosen.

With the advent of the PSLV came the need to develop much bigger motor cases for the solid rockets; liquid engines for the second and fourth stages; specialised tanks for carrying liquid fuels; development of fuel pumps; bigger heat shields and structures for the equipment bay, and so on. The demand for the total propellant requirements and the chemicals also increased manifold.

Similarly, at the launch range in SDSC, ISRO had to develop large ground handling systems and facility for integration of stages as well as the whole launch vehicle; processing equipment for the preparation and casting of the solid propellant; storage, handling and filling the liquid propellants; the associated test stands; the launch pad, the Mobile Service Tower, the complex launch control, command and communication facilities and safety systems. Participation of industry correspondingly increased.

For light alloy fabrication, HAL was a natural choice, and ISRO was successful in persuading HAL to provide its capacity and also partly funded its assembly-level facility. This arrangement led to the birth of a dedicated HAL-Aerospace Division, a milestone in ISRO–industry collaboration.

The list of other industrial partners included many illustrious names like Mishra Dhathu Nigam (MIDHANI), Rourkela Steel Plant, Bharat Heavy Electricals Limited (BHEL), Echjay, Jindal, HAL Foundry and Forge,Vishnu Forge, Ramakrishna Engineering, Walchandnagar Industries Ltd. (WIL) and L&T, Godrej, KELTEC, MTAR, Taneja Aerospace, Venkateswara Industries, Kobashi Machine Tools, PYN Precision Components, Art Industrial School, Kannan Industries, JoJo Industries, PSG, and so on.

ISRO spearheaded numerous innovations in the field of materials and special chemicals, successfully producing them with its industry partners. This involved collaborative efforts among ISRO, research laboratories such as Defence Metallurgical Research Laboratory (DMRL), and process innovators like MIDHANI. The development and use of Indian Maraging Steel for the PSLV booster case, the titanium alloys for tanks and gas bottles and a variety of other light alloys, special magnetic materials, and materials compatible with the cryogenic engine and stage are some examples of such indigenous developments. Carbon cloth and high silica cloth are other examples of ISRO's persistence in developing industrial production capability.

The challenge of embargo

During the development of the GSLV, ISRO had to face the so-called embargo by the USA, as a result of which the Russians were forced to renege on their agreement to transfer technology for the cryogenic stages. Because of ISRO's emphasis on self-reliance right from the beginning, the embargo did not derail any programme, though it did delay the indigenous development of the cryogenic engine and stage. The net result was that ISRO emerged stronger. There had been an interesting episode in this connection. When the sanctions were in place on ISRO, Godrej, which had been providing fabrication support to ISRO's launch vehicles, also faced the embargo that affected its market for other product lines. But, despite its losses, it did not withdraw its support to the national space programme, based on its conviction that what it was doing was right. Godrej deserves a pat on its back for this display of national spirit.

One-meter-diameter motor case welding at Anoop Engineering Ltd., Ahmedabad. These motor cases have been in use since the SLV-3 days.

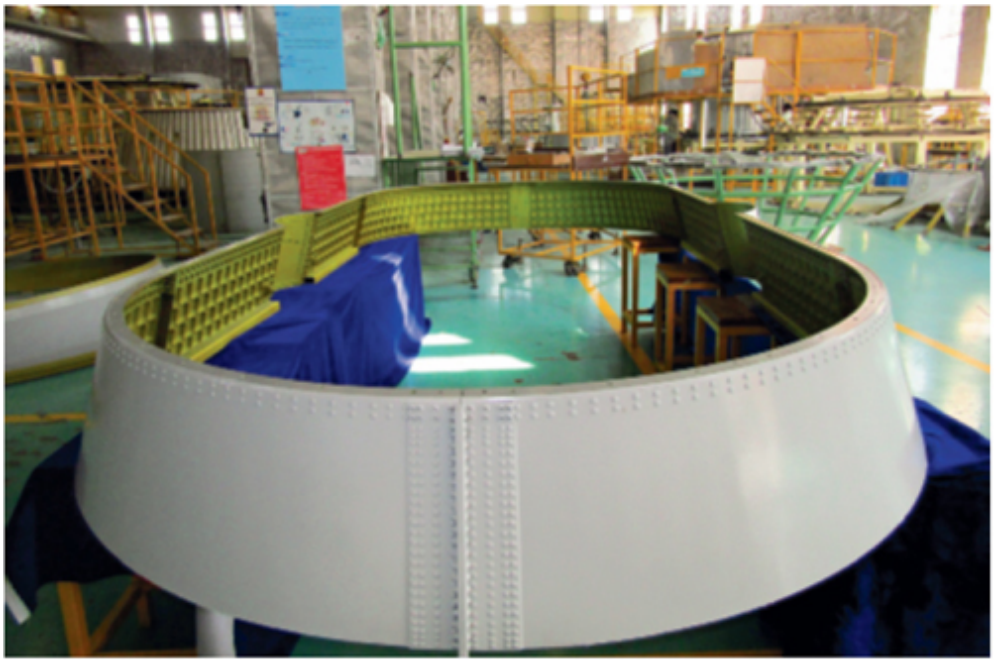
The core liquid stage of the GSLV Mk III being tested at ISRO Propulsion Complex at Mahendragiri in Tamil Nadu. These engines are manufactured at various industries. The test stand was also made by the industries. The fuel for the liquid propellant (unsymmetrical dimethyl hydrazine) is manufactured at Andhra Sugars Ltd., Tanuku, Andhra Pradesh.

A scene from a foundry

PSO-XL strap-on motor case (of one-metre diameter) the first hardware made at SVAPL, Hyderabad, being handed over to S Ramakrishnan, (eighth from left) by VLN Reddy (seventh from right). Ramakrishnan is flanked by Roy M Cherian and Koshy M George.
For less-than-one-meter-diameter hardware, the industries are SVMEET, SEC Hyderabad, LEGEND, TAAL and GAVCES.

Water tank for the L110 stage for GSLV Mk III.

LH_2 propellant tank for the cryogenic upper stage.



GSLV Mk III L110 flare shroud assembly at HAL-Aerospace Division.

GSLV heat-shield sub-assembly at HAL-Aerospace Division.

The PSLV second-stage propellant tank is made at HAL-Aerospace Division.

Preparing for the operational era

The communication satellite system, INSAT-1, was the first to usher in operational services to the country in telecommunications, television distribution, and weather observations, while IRS-1A performed the same service in remote sensing. The development of a variety of ground equipment needed by users of these services and applications such as disaster communications and educational broadcasts was spearheaded by the Space Applications Centre (SAC) at Ahmedabad. These efforts by SAC finally led ISRO to gain a leadership position globally, especially in the remote sensing area. SAC also evolved a new model of industrial interface which was characterised by joint development approach, thereby reducing the know-how transfer time. Industries such as BEL (Ghaziabad Unit), HAL, Electronics Corporation of India Limited (ECEL), GCEL, Avantel, Astra Microwave, Semiconductors Limited, VXL Technologies, Weiler International Electronics, General Optics (Asia) Limited, and so on, contributed; some of them were involved from the initial stages of development. Know-how transfers from SAC played a key role in energising space application markets.

The operational era also brought challenges to the ISRO Satellite Centre (ISAC) and its partners in industry. ISRO's satellites had to grow in size, mass and power capabilities as well as in their complexity and efficiency. Their stabilisation and attitude control requirements, data transmission capabilities, demand for new mechanisms for on-orbit deployment, thermal design complexity, orbital operational life expectations, operational demands as well as reliability needs have been growing continuously and have kept pace with global developments. These were the challenges ISAC grappled with in shaping industrial support strategies. For structures and thermal control aspects, excellent support was developed through HAL and home-grown small and medium enterprises like Avasarala Automation. ISAC through its persistent efforts and cooperation had industrialised the solar panel assembly and manufacture through BHEL in Bangalore. Similarly, ISRO's Liquid Propulsion Systems Centre (LPSC) successfully developed industrial collaboration with BHEL's unit at Ranipet for delicate machining of satellite propellant tank parts made of titanium metal alloys needed for satellite propulsion. Other industries involved were KCP in Chennai, Central Tool Room and Training Centre, Lakshmi Technology and Engineering,

Veekay Industries, MTAR, Brahmos Aerospace Thiruvananthapuram, and ASAKO, among others.

SDSC in Sriharikota, the spaceport of India, has built, over the years, massive infrastructure that supports all of ISRO's launches, besides solid propellant production and liquid and cryo-propellant handling systems.

The facilities include two launch pads with their complexes, including lightning protection systems, vehicle assembly building with a mobile launch pedestal, mission control centre, modern communications and computation infrastructure, telemetry, tracking and telecommand network, etc. All these facilities were built with industry participation, some of them on a turnkey basis.

Support from administrators

In the very early years of ISRO, a pioneering study was done on contract systems that could facilitate industry contributions for even risky developmental activities, contracts that could accommodate long-term commitment to industry, and contracts that could be compatible for a collaborative mode of working between ISRO and industry. For those times, this was a unique feature for a government organisation that was nurtured by top-level leaders, managers and bureaucrats in the organisation. In other words, this culture was the result of a good understanding between the technical and administrative personnel of ISRO and the Department of Space (DOS). One hopes this culture will prevail in the future.

The funding schemes adopted with the industries, mentioned earlier, were all obviously alien to typical government set-ups and institutions and required careful understanding and handling for proper implementation. Here, the very positive and important roles played by the Department of Space and bureaucrats such as the Joint Secretary and Additional Secretary require a very special mention.

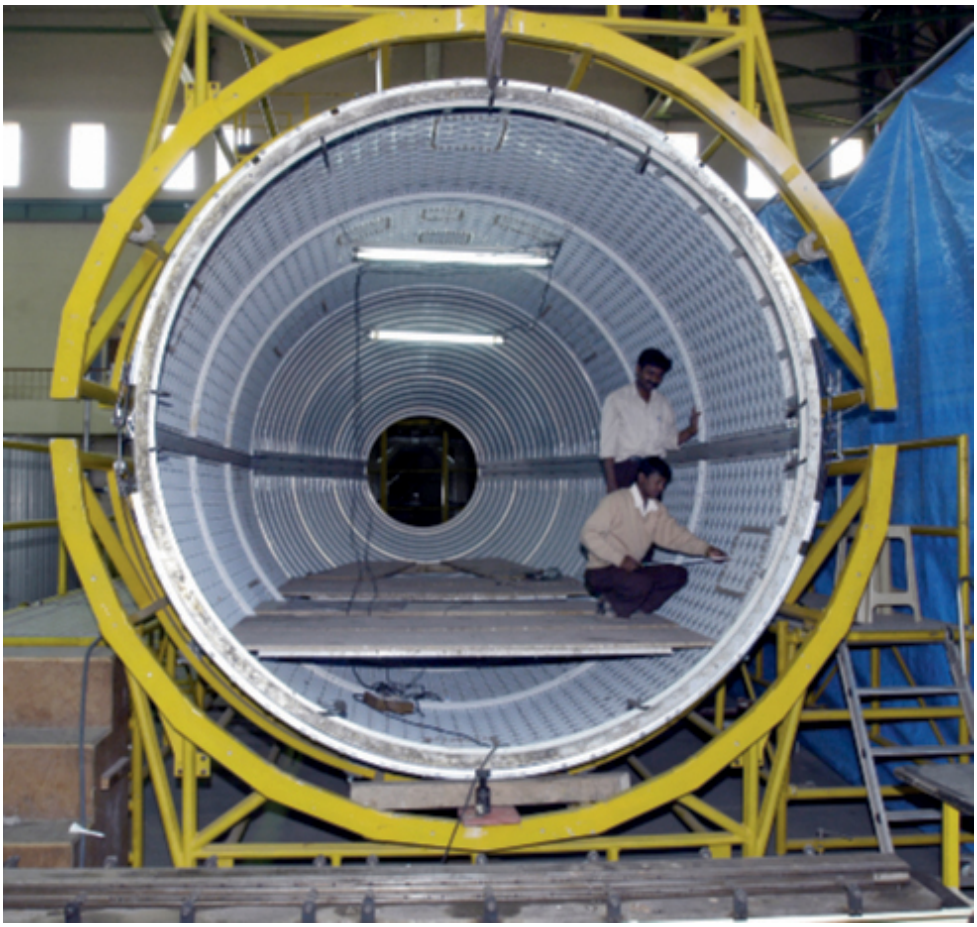
It is only proper here to quote from the article "The rocket science of Governance" from the Bangalore edition of the magazine *India Today,* dated 8 April 2004.

Quote

“Red tape has drained us of the capacity to think of even small, innovative solutions. To change all these would require reforms which are massive, across the hoard, simultaneous on all fronts, and which are sustained. None of these four things is allowed by the system as a whole. We must look around. You have islands like the ISRO which have worked in a completely different culture”.

Unquote

★★★



PSLV heat-shield assembly after vertical coupling at HAL-Aerospace Division.

L40 Inter Tank Structure (ITS) assembly at HAL-Aerospace Division.

GSLV 1/2M (middle segment of the hardware that connects stages 1 and 2) assembly at HAL-Aerospace Division.

The cryo-engine for GSLV Mk III – a view. Manufacturers include MTAR (Hyderabad), Godrej (Mumbai), HAL (Bangalore) and LTE (Coimbatore).

K Radhakrishnan receiving a memento from the Managing Director, Bay Forge, after visiting the ISRO-funded facilities. Also seen are PP Sinha, Koshy M George and Sankaravelayudhan.

AS Kiran Kumar on the Aeroshop floor, Walchandnagar Industries Ltd. (WIL).

The Angular Motion Simulator was made at L&T, Powai. Seen are K Radhkrishnan and TJ Ravindran.

Core-alone version of the PSLV (no strap-ons) on the launch pad. The Mobile Service Structure, seen on the right, was fabricated by Triveni Structures.

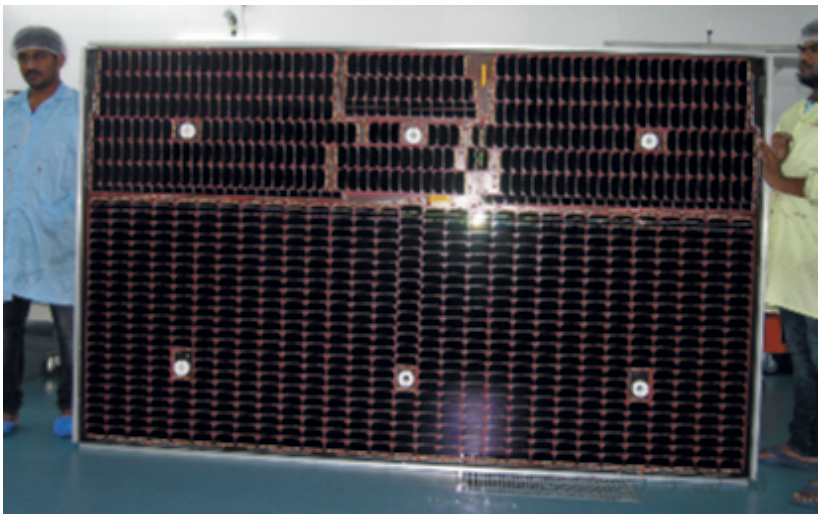
PSLV on the second launch pad. The second launch pad complex was built by MECON Ltd., Ranchi, on a turnkey basis. The Umbilical Tower was fabricated by Bhilai Engineering Corporation.

G Madhavan Nair (checked shirt) during a visit to the ISRO-funded Titanium Sponge Plant at KMML, Chavara, Kerala.

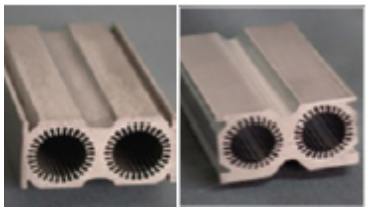
Solid motor S 200 mandrel in the background. S Ramakrishnan (fifth from left) and VLN Reddy (extreme right) can be seen.

Formal inauguration of Titanium Sponge Plant at KMML, Chavara, Kerala. PS Veeraraghavan and T Balakrishnan, Principal Secretary, Industries (Kerala), are also seen.

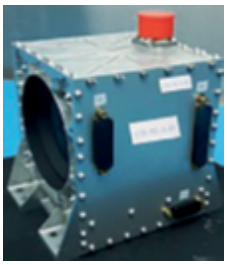
The carbon composite heat shield for the GSLV Mk III was also manufactured in the industry.



GSAT-31 solar panel from HAL, Bangalore.



Heat pipes from Avasarala Technologies Limited.



Mark II Star Sensor manufactured by Ananth Technology Ltd., India.

Lithium–ion battery from BHEL.

Star sensor optics module manufactured by System Controls, India.

Surface Mount Technology (SMT) assembly at Centum Electronics, Bangalore.

SMT re-flow soldering at Centum Electronics, Bangalore.

Crew Module Atmospheric Re-entry Experiment in a clean room before its launch. This was fabricated at HAL, Bangalore.

PR Pisharoty

ISRO in the Service of the Nation

Introduction

"To us, there is no ambiguity of purpose", wrote Vikram Sarabhai, referring to the "… application of advanced technologies to the real problems of man and society which we find in our country." Since then, ISRO has meticulously followed this creed enunciated by the visionary. Sarabhai also recognised the need to involve various government departments and policy makers in decision-making with regard to space applications.

Prime Minister Indira Gandhi dedicating INSAT-1 to the nation (February 1984). On her right: AE Muthunayagam. To her left: PP Kale and KPM

Bhat

Government of India
Department of Space
राष्ट्रीय अधिवेशन
National Meet
अभिशासन व विकास में
अंतरिक्ष प्रौद्योगिकी आधारित साधनों एवं अनुप्रयोगों का संवर्धन
Promoting Space Technology based Tools
and Applications in Governance & Development
September 07, 2015
Vigyan Bhawan, New Delhi

Prime Minister Narendra Modi addressing the valedictory session of the National Meet at Vigyan Bhavan 2015. Of the 157 projects that emerged from this meet, 126 have progressed as scheduled.

Thus, he invited around 200 parliamentarians and Heads of Departments to attend a lecture by PR Pisharoty on remote sensing at the Constitution Club, New Delhi. Only around 100 attended the lecture, but a beginning had been made. This was in the late 1960s.

Sarabhai's idea was structured into ISRO by his successor, Satish Dhawan. He formed two committees: the INSAT Coordination Committee (ICC) and the Planning Committee of the National Natural Resources Management System (PC-NNRMS). These committees have Secretaries of various Government Departments as Members. Thus, Government functionaries have a say in what applications ISRO should pursue. These committees also ensure total transparency about what ISRO does.

More recently, the Department of Space (DOS) had organised a one-day National Meet on 7 September 2015 at Vigyan Bhavan, New Delhi, on "Promoting Space Technology-based tools and Applications in Governance and Development." It was attended by 1200 delegates from across 60 Central Ministries and Departments, 23 States and 5 Union Territories. The

Prime Minister of India, Narendra Modi, addressed the concluding session of the Meet by "emphasising the need for new initiatives in all areas of Governance using space technology applications."

All the applications of space technology flow from three types of ISRO satellites: the INSAT family of communication satellites, the remote sensing satellites and the navigation satellites.

A simple but essential concept

'Bird's eye view' is a phrase commonly used to suggest that birds in flight can see more of the Earth than people on the ground. The idea is the higher the altitude, the bigger the part of the Earth's surface you can see. Thus, satellites in orbit see great stretches of land.

A communication satellite in the geostationary orbit at an altitude of 36,000 km can "see" over 40% of the Earth's surface. Almost all applications of space technology are the result of this vantage location of satellites. Thus, satellites give us the "big picture".

For convenience, we describe these applications under two headings: communication satellites and remote sensing satellites, even though there is overlap between the two.

Applications: Communication satellites

We do not intend to cover all possible applications; instead, we deal with some typical ones.

The basic payload in a communication satellite is the transponder. For example, a TV programme recorded in, say, Delhi is sent to the communication satellite at a height of 36,000 km. The transponder in the satellite receives this programme, amplifies it and then broadcasts it down so that everyone in the country can see the programme simultaneously.

Some of the applications are fully operational and the services are available across the country. An outstanding example is television. Before the advent of INSAT-1 in 1984, there were only a handful of TV channels, but now

there are several hundreds. There is hardly any place in the country where TV is not available. For this, both Doordarshan (DD) and private operators are responsible. Be sure to thank communication satellites the next time you watch India play a cricket match in a faraway place like the West Indies. All the DTH (Direct to Home) dish antennas you see on the rooftops of houses are pointed towards communication satellites. Similarly, OB (Outdoor Broadcast) vans, seen frequently on the streets, are the means through which satellite news gathering is carried out to bring live coverage of events right into our homes.

Another example is the VSAT (Very Small Aperture Terminal) networks. There are over 2,74,000 VSAT networks, which serve businesses such as bank ATMs, stock exchanges, telecom backhauls, etc. In remote areas and islands, VSAT is the prime choice for connectivity.

When disasters like super cyclones and earthquakes disrupt communications through mobiles, internet, and so on, only the Mobile Satellite Service comes to the rescue. In this, a handheld terminal (satellite phone) provides connectivity to the outside world. One can use this facility from any location in India. These services are used mainly by government agencies.

When, in 2004, ISRO launched EDUSAT, 87% of all schools were in villages and 19% of them were single-teacher schools. Worse still, the growth rate of teachers had fallen alarmingly in 1950–1990, from 5.6% in 1952 to 4.6% in the 1960s, to 2.7% in the 1970s before it fell precipitously to 1.4% in 1984–1990. Thus the need for EDUSAT, a tool for distance education, was (and is) beyond question. Students located in geographically dispersed areas could in real-time listen to lectures delivered by competent teachers in big cities.

This is **tele-education** and it is applicable to primary, secondary and higher secondary levels as well as to technical education. Under this programme, over 56,000 classrooms in the country have been connected to the network. It is estimated that around one crore and fifty lakh students benefit each year from tele-education. Currently, there are 47 tele-education networks in the country.

In 2010, EDUSAT completed its mission life but ISRO continues to provide tele-education facility through other satellites of the INSAT family.

A young woman accessing a lecture through the EDUSAT network.

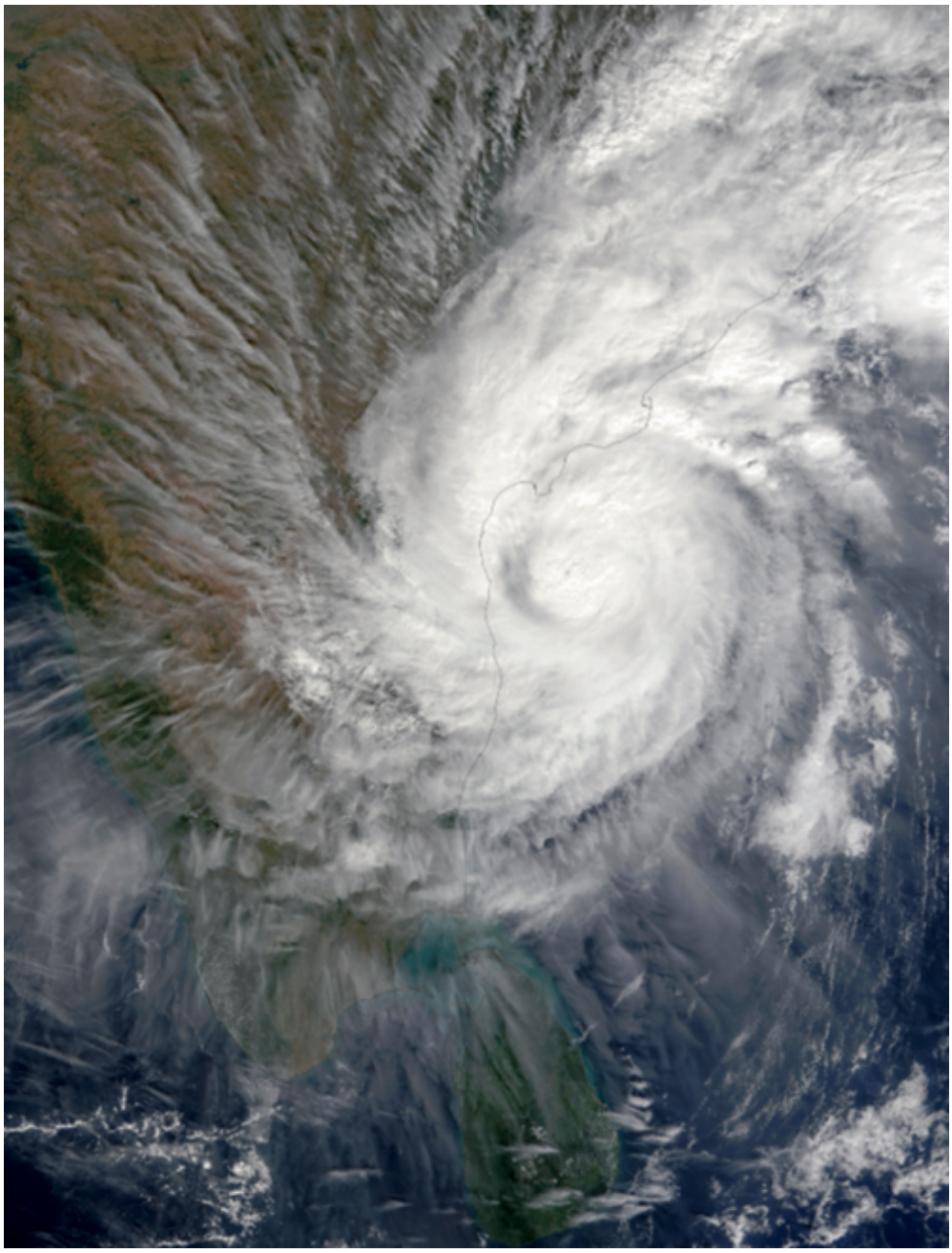
During the INSAT-1 period, Komal GB Singh was in the limelight for 10 years and became a household name for her news-reading skills on Doordarshan, the national TV channel.

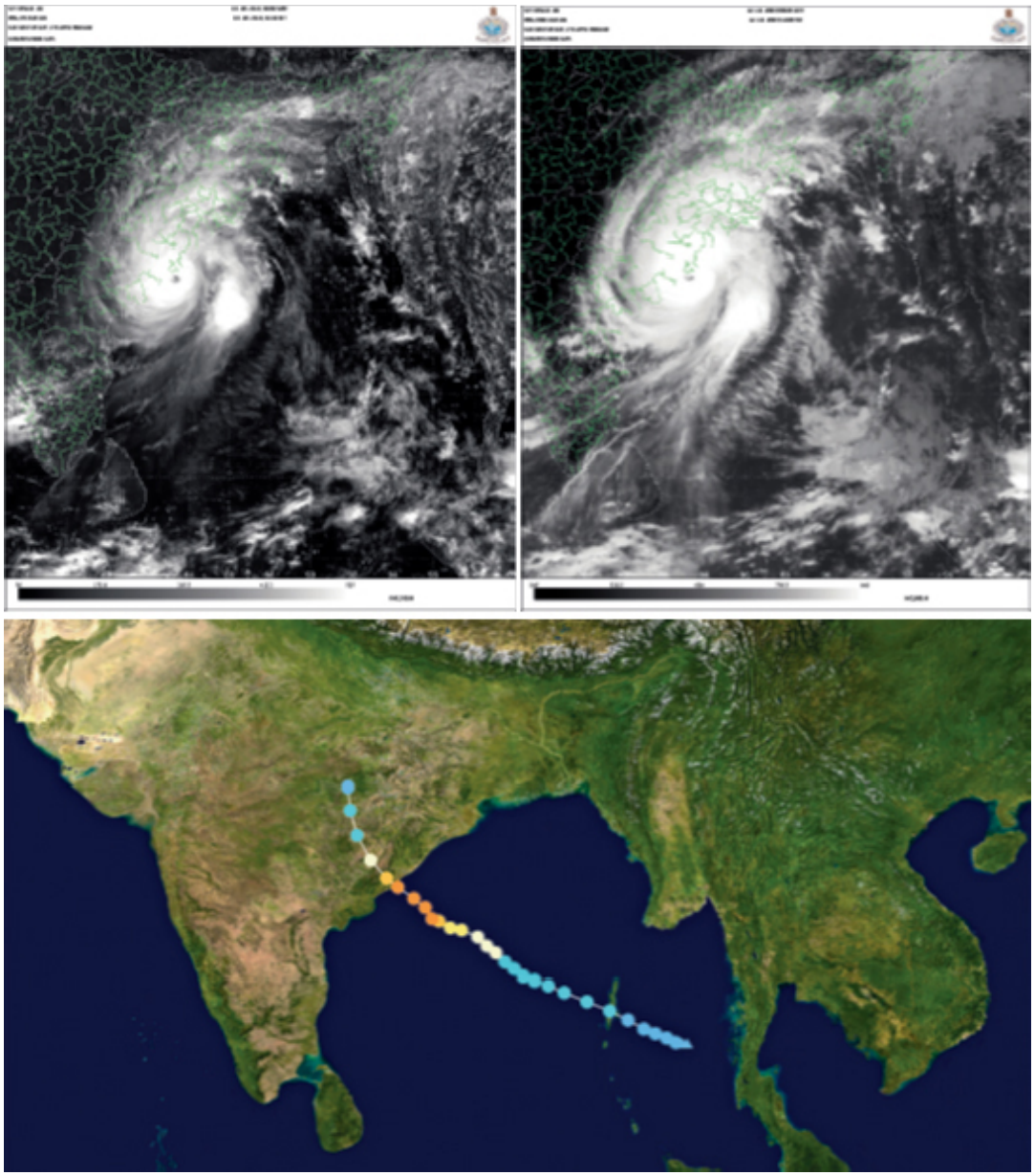
Outdoor Broadcast (OB) vans on their way to covering an event. Satellite news gathering is common today (Source: Mirchi 9).

Commissioning of Mizoram EDUSAT network on 24 November 2017 by H Rohluna, Minister for School Education (sitting third from left). Virender Singh, Director of DECU at the mike.

PV Sindhu in action. Thanks to communication satellites, we can watch live action in sports from anywhere in the world. Courtesy: Pratik Behera.

Dish antenna for the Jhabua Development Communications Project, India. Mobile satellite service is of great help to our Army (Source: BSNL).
A new telemedicine node was recently installed at the forward area. Currently, there are 130 telemedicine nodes operating in the country.

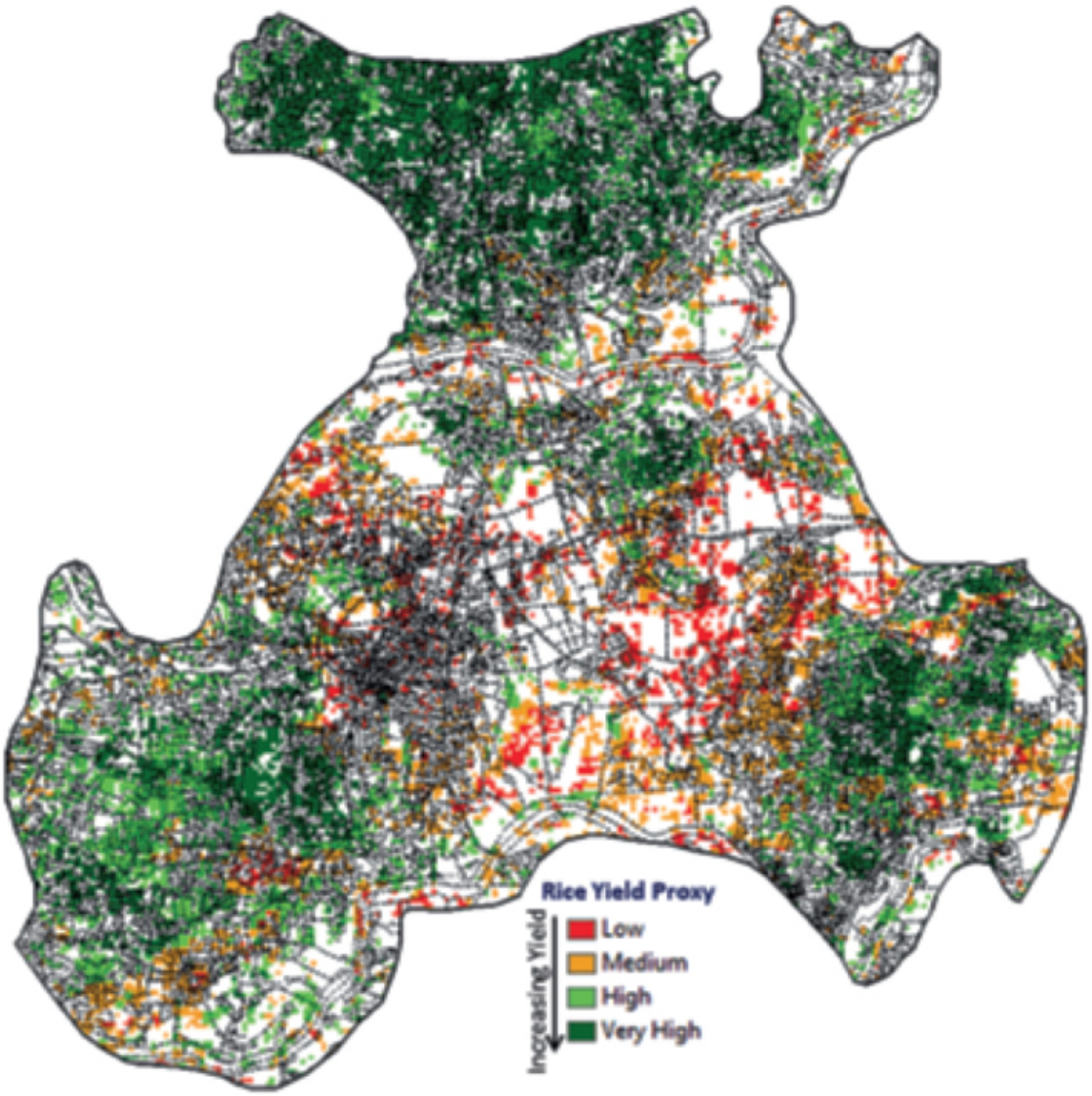




Tracking cyclone Hudhud, which hit the east coast of India in 2014.

Coast guard in action.

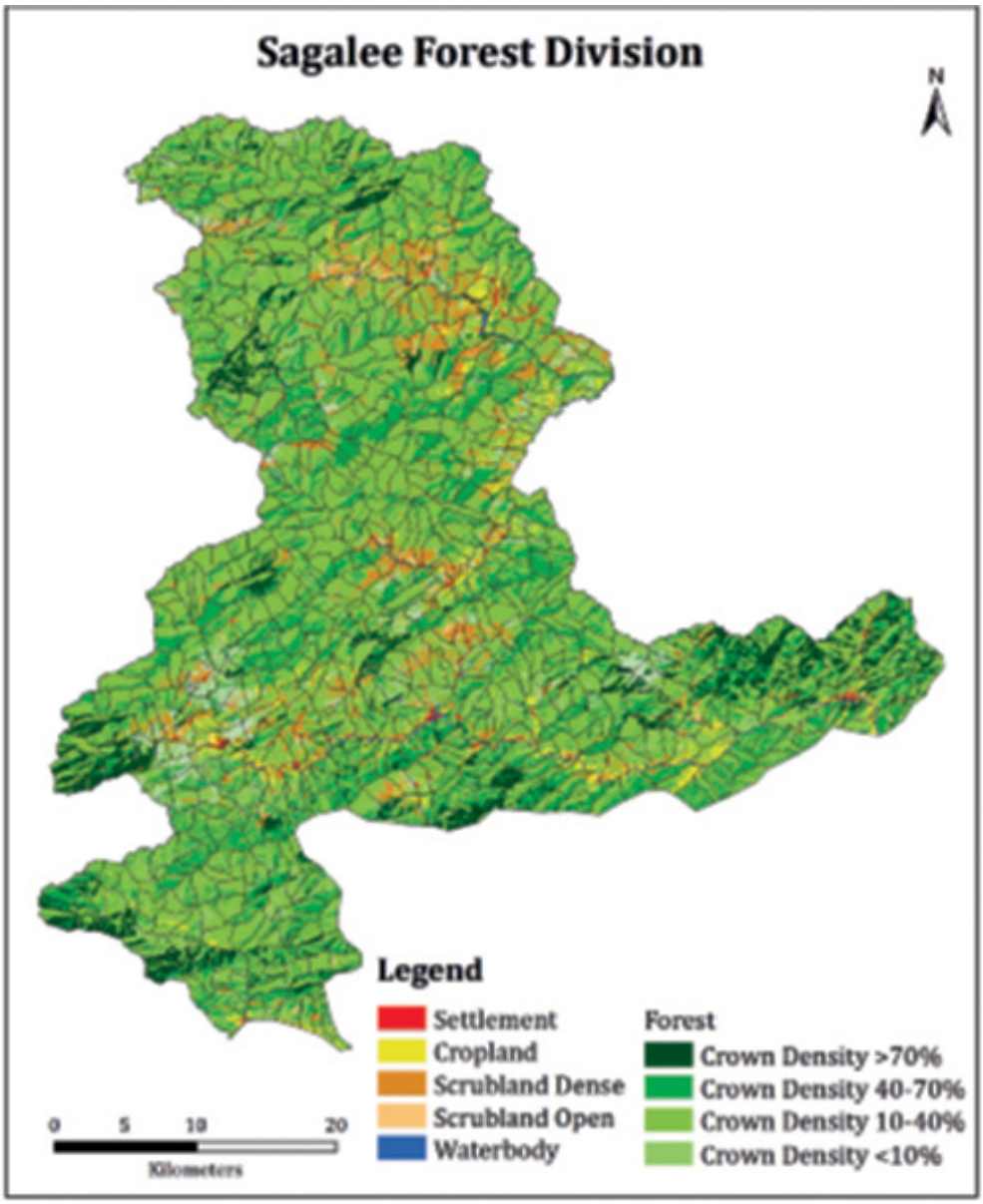
Radar Imaging Satellite (RISAT) images of fine-resolution strip map 1 (FRS 1) and synthetic aperture radar (SAR) images of Mumbai.



Crop insurance is a lifeline for farmers. A technique called 'smart sampling' has been developed jointly by the Government of Odisha and ISRO to improve crop yield estimates in insured units of farmland. Picture shows various levels of crop yield in a smart-sampled plot.

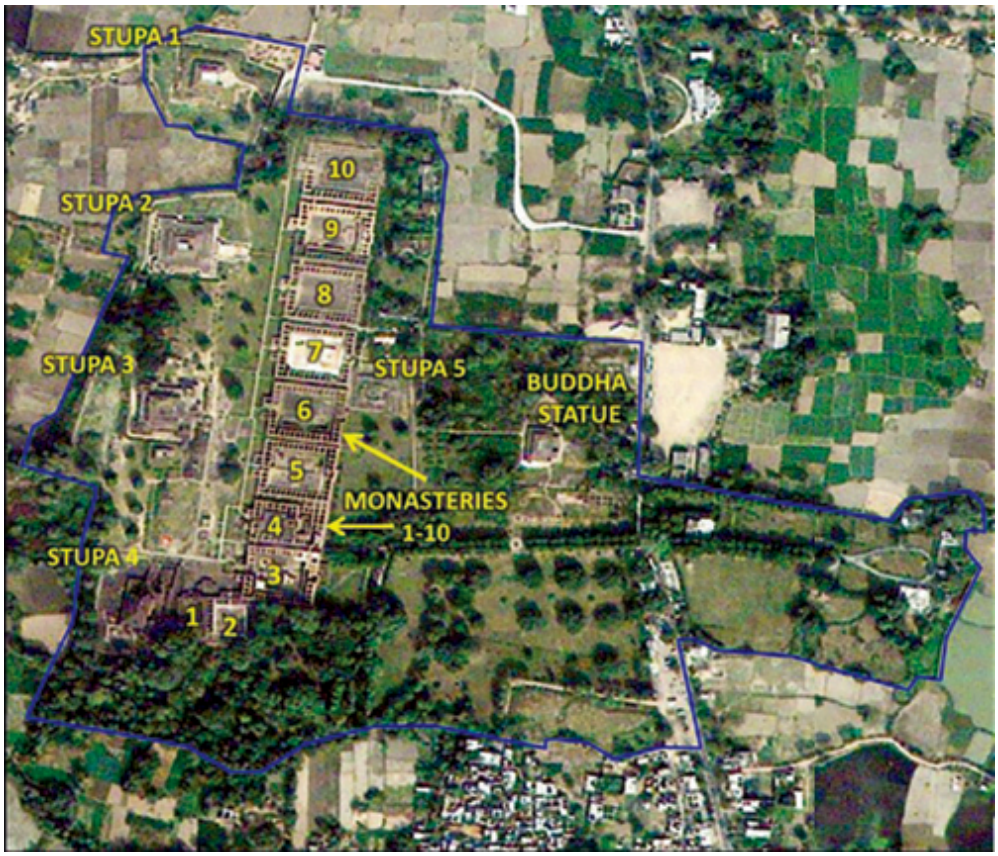
Satellite image of mango and palm plantations in the Krishna District of Andhra Pradesh.

A citrus (acid lime) plantation in Nellore, Andhra Pradesh.



Deforestation: Severity of forest cover removal and degradation is evident on the edges of the Siwaliks, adjacent to the plains around Sonitpur and its surroundings in Assam. The degradation endangered ecological processes and services as well.

Hussain Sagar is a picturesque, heart-shaped lake nestled between the twin cities of Hyderabad and Secunderabad. A sprawling artificial lake that holds water perennially, the Hussain Sagar was built on a tributary of the Musi river in 1562 to meet the water and irrigation needs of the city. It was among the largest artificial lakes in Asia, although the lake area has shrunk by a large extent over the years. In the image, the little white dot seen inside the lake is one of its major attractions: a finely sculpted 18-m-high and 350-tonne monolithic statue of Gautam Buddha stands on a rock.



Nalanda is an ancient Buddhist site, a centre of learning, dating back to the 5th or 6th century BC. Based on findings by Buchanan in 1838, General Alexander Cunningham identified the site for the first time in 1861–62. Later, from 1915 to 1937, the Archaeological Survey of India (ASI) excavated the site, and the present site of 1.5 sq km is being maintained by the ASI. (Photo source: Wikipedia).

This very-high-resolution CARTOSAT-2 image shows clearly the extent and layout of Nalanda, which includes 10 monasteries and five stupas/temples.

Similar in concept to tele-education is **telemedicine,** which connects remote district hospitals/health centres to super-speciality hospitals In cities. Through video conferencing, telemedicine creates a virtual environment for emotionally connecting the patient to the specialist in a faraway hospital.

Currently, the telemedicine network of ISRO covers about 384 hospitals, with 60 speciality hospitals connected to 306 remote/rural/district/medical college hospitals and 18 Mobile Telemedicine units. The Mobile Telemedicine units cover diverse areas of Ophthalmology, Cardiology, Radiology, Diabetology, Mammography,General Medicine and Women and Child Healthcare, These numbers show that telemedicine in the country is in its infancy. Central and state governments as well as private hospitals have

to pitch in to provide the necessary infrastructure to make telemedicine a success across the country.

Meteorology benefitted the most from satellite technology. News bulletins invariably end with weather reports. Meteorological predictions have become more accurate. Come May or June, everyone, including our economists, look forward to what the Met Department has to say about the monsoon. Meteorologists can also track cyclones right from their birth, follow their evolution, predict their intensity and also estimate when landfall will occur. These advances have saved many lives. When, on 29 October 1999, a super cyclone hit Orissa (now Odisha), nearly 10,000 people died. But when, on 11 October 2013, Cyclone Phailin hit Andhra and Odisha, the death toll was 43. To be fair, we should note that this was possible not only because of satellites but also because of (1) vast strides made by our meteorologists in modelling, (2) alertness of local and central governments, (3) rescue teams from the police, navy and army and (4) help from other agencies, including foreign ones.

Normally, rescue follows disaster. But satellites make it possible to be proactive and search the globe for possible distress signals! Called search and rescue, this is done through an international programme, COSPAS-SARSAT, in which India participates. From 1990 till March 2013,78 distress events occurred in the Indian service area and 1931 lives were saved under this programme.

Applications: Remote sensing satellites

The Basic payload on-board a remote sensing satellite is the imaging system (camera). In addition, remote sensing satellites in sun-synchronous orbits can take pictures of the same area under the same solar illumination conditions repeatedly for years. Further, the modern imaging systems can “see” both below and above the narrow band of the visible part of the electromagnetic spectrum. All these properties allow us to use remote sensing imagery for a variety of purposes, of which some examples are described below.

Agriculture

The importance of agriculture in our country can never be overemphasised. Nearly 70% of rural employment and 18% of GDP comes from agriculture (2012 data). The remote sensing space systems of ISRO provide the following information: (l) crop production forecasting, (2) crop intensification, rotation and crop system analysis, (3) mapping of waste land and salt-affected soils and (4) information related to horticulture.

Forestry

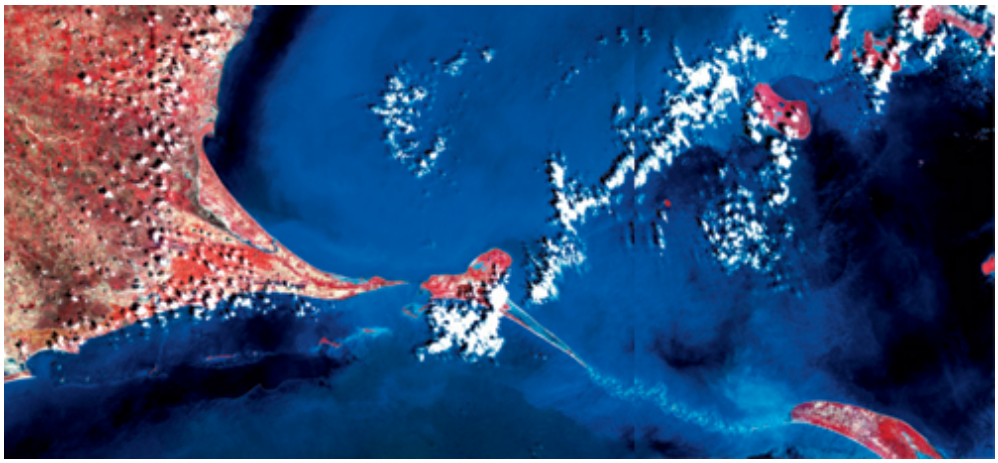
In 1983, the first national-level mapping of forest cover using remote sensing data was carried out. It showed enormous levels of deforestation. Since then, the Forest Services of India has been undertaking such mapping every two years and presenting the results to Parliament. From remote sensing data, one can easily assess how far afforestation efforts have been successful.

Water resources

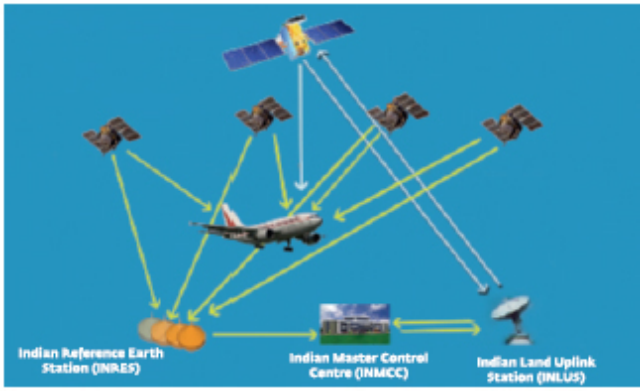
Information on the water resources of the country is varied; it ranges from mere inventorying and monitoring surface water bodies to more complex ones like irrigation performance, groundwater exploration, snowmelt runoff forecasts, flood inundation mapping and forecasting, reservoir sedimentation, etc. In all these areas, images from ISRO satellites have been used routinely. For example, a national-level hydro-geomorphic mapping carried out using the geographic information system as part of the Rajiv Gandhi National Drinking Water Mission was hugely successful. The success rate was over 90% when wells were drilled based on groundwater prospect maps prepared using remote sensing data. These are all indicators of what one can do with space data. Of course, this alone cannot solve all the water-related problems our country faces!

Water resources information system of India

This is a joint project of the Central Water Commission and ISRO. It was conceived as a single-window solution to the problems of obtaining authoritative data on India's water resources, along with other related information including geographical details. The system has information on surface water, groundwater, hydrometeorology, water quality, snow cover, glaciers, inland navigation waterways, inter basin transfer links, etc. All this information can be accessed through a variety of tools. One of them, known as Bhuvan, is described later.

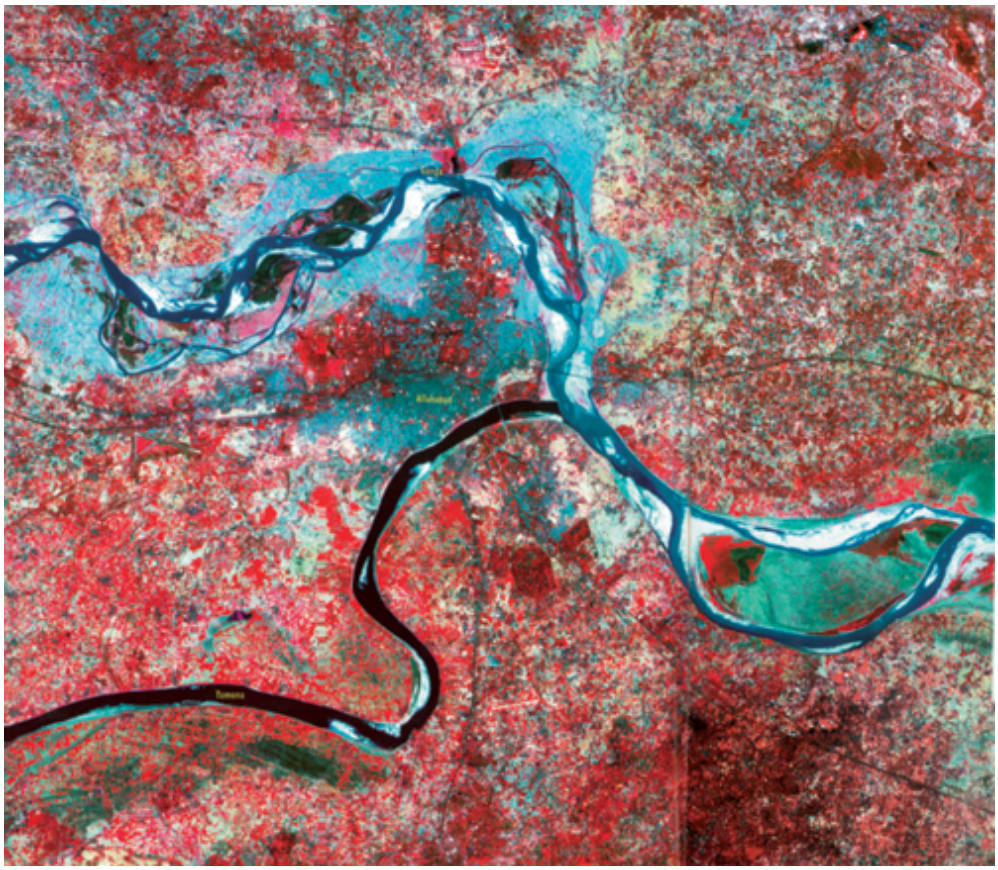


A bird's eye view of the Gulf of Mannar shows the carat islands as white caps scattered over the light blue shallow waters at the confluence of the Bay of Bengal and the Indian Ocean. This is an important Marine National Park of India situated in the southern Bay of Bengal between India and Sri Lanka. The region is rich in marine biodiversity, with several hard corals, sea turtles, sharks, dugong and dolphins.



Schematic of GPS-aided GEO Augmented Navigation (GAGAN). GAGAN has helped modernise our communication, navigation and surveillance systems. It also helps aeroplanes land safely in marginal weather conditions and in 'difficult approach air strips'.

Urban sprawl: A composite of the Banaras Hindu University campus on the right (planned) and Varanasi town (unplanned) on the left.



The Ganga meets the Yamuna at Allahabad.

Geological applications

In the past, the Geological Survey of India (GSI) had to depend solely on people working at the site for collecting data. Now, GSI has an ally in remote sensing. Both central and state government departments are now using remote sensing data in conjunction with field data to identify geological structures. An exotic example is Kimberlite, a type of rock. When this occurs in the Earth's crust as vertical structures, they are known as Kimberlite pipes. They sometimes have diamonds in them! Similarly, one can identify coal fields, coal-fire-affected areas, and so on, using satellite images.

Conservation of heritage sites

The conservation of world heritage sites, ancient monuments and archaeological sites is of national importance and helps in the development and promotion of tourism, which is one of the major engines of economic growth. The systematic database of heritage sites and Site Management Plans generated using space technology will help us make informed decisions regarding the conservation, preservation and monitoring activities of the site. A pilot study has already been carried out for Hampi World Heritage Site, Karnataka. The full potential of this application has yet to be established and utilised.

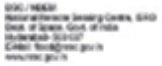
Coastal zone

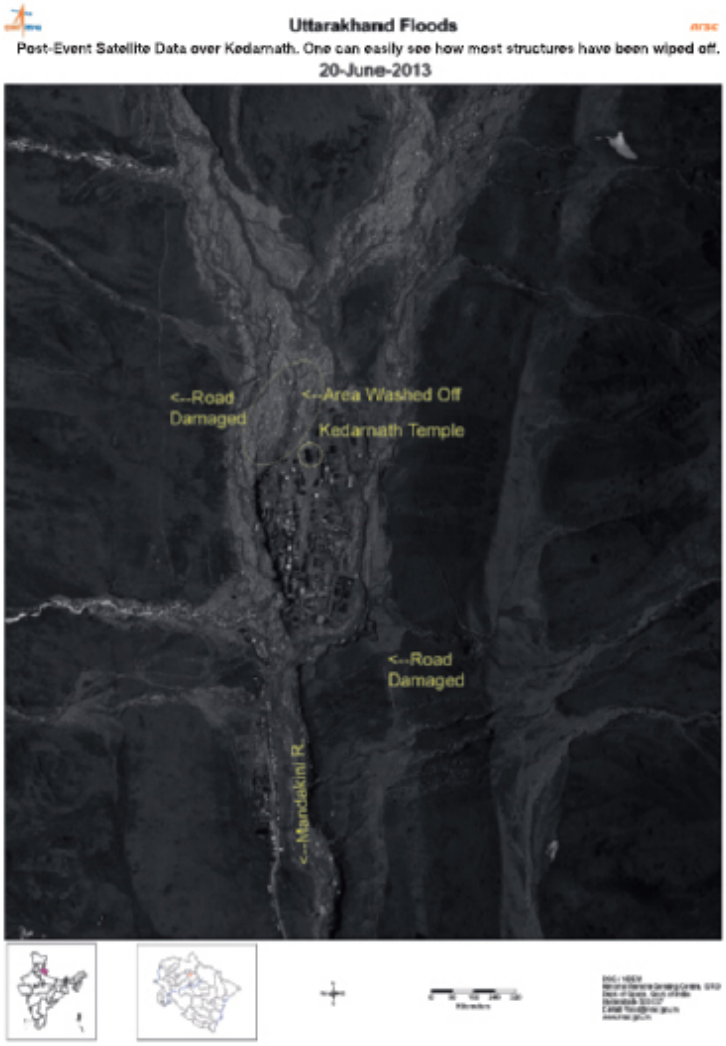
Our coastal zone is 7500-km long. Nearly a quarter of our population lives within 60 km of it. From satellite data, one can extract information on coastal wetlands, land use and land cover, critical habitats (mangroves, coral reefs), high and low tide lines, shore line changes, etc. Satellite data also helps in selecting potential sites for brackish water aquaculture and coastal zone management.

Uttarakhand Floods

Pre-Event Satellite Data over Kedarnath

nrsc





The Ministry of Environment and Forests has authorised the use of satellite data in providing environmental clearances for projects and in demarcating the Coastal Regulation Zone. An inventory carried out during 2005–07 showed that the total area of our country under mangroves was 4,95,620 hectares. Mangroves are important as they help in the production of detritus and organic matter, and in recycling nutrients which enrich coastal waters.

Fisheries

By monitoring sea surface temperatures and ocean colour using satellites, it is possible to predict where aggregation of fish occurs. The technique developed for Potential Fishing Zone (PFZ) forecast (up to 2–3 days in

advance) has been validated by a number of ship campaigns carried out in Indian waters. Results have shown a success rate of 70–90% in PFZ forecasts. Now, PFZ advisories are being made available daily in local languages.

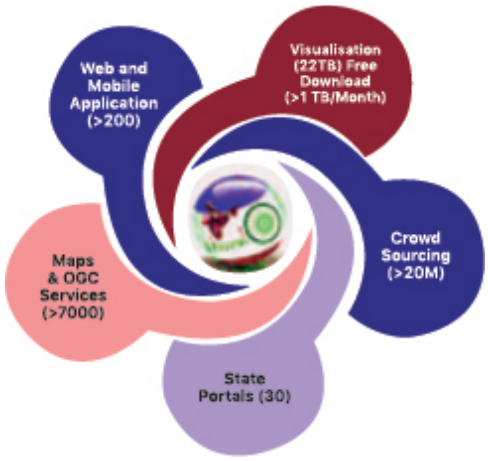
Kerala Floods 2018; real-time images from ISRO's remote sensing satellites were of great help in reaching aid to affected areas. (Source: Team bhp.com).

Bhuvan

Bhuvan is ISRO's online geoportal through which one can access geographical and other associated information across the country. It offers services related to climate studies and near-real-time disaster management.

Disaster management has three broad phases: pre-warning, during the event and post-disaster, and Bhuvan provides services during all these phases. For example, Bhuvan services were used extensively during the Uttarakhand (Kedarnath) Disaster of 2013.

Bhuvan Geospatial Gateway


Web and Mobile Application (>200)
Visualisation (22TB) Free Download (>1 TB/Month)
Crowd Sourcing (>20M)
Maps & OGC Services (>7000)
State Portals (30)

Subsequently, all major disasters in the country are being monitored online. Examples include a series of cyclones in 2013, particularly the Phailin; major forest fire events in Nagarahole and Bandipur in Karnataka followed by the Thirumala forest fire in Andhra Pradesh during February 2014; major floods in Jammu and Kashmir which devastated the state and was declared as a national disaster; and Cyclone Hudhud that hit Andhra Pradesh. A more recent example is the Kerala Floods.

Bhuvan's crowdsourcing app was used extensively in the reconstruction work undertaken by the government following the Uttarakhand disaster.

Other examples where Bhuvan has helped governance are online Urban Master Plan preparation, planning of Integrated Watershed Management Program (IWMP) and decentralised planning and development at Panchayat level.

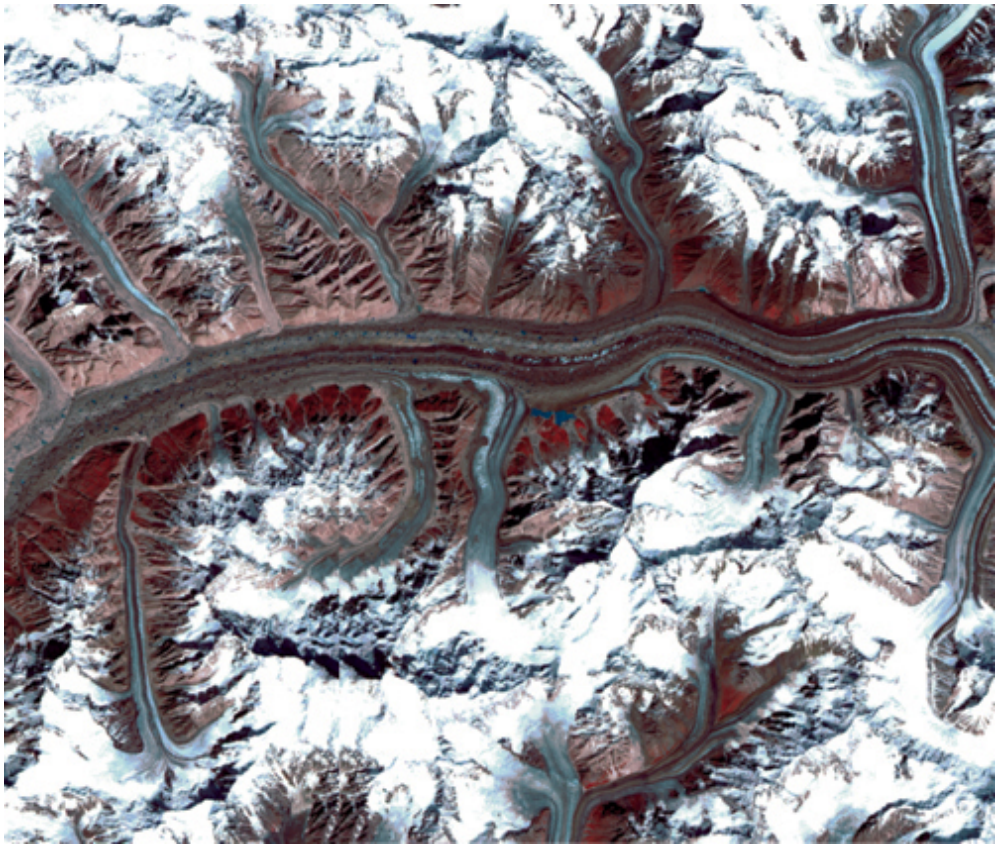
Navigation

The family of navigation satellites of ISRO is a relatively new one. It is the regional counterpart of GPS and GLONASS (see Chapter 4). Applications include terrestrial, aerial and marine navigation, vehicle tracking and precision timing. Further, these satellites bolster some of the applications described above.

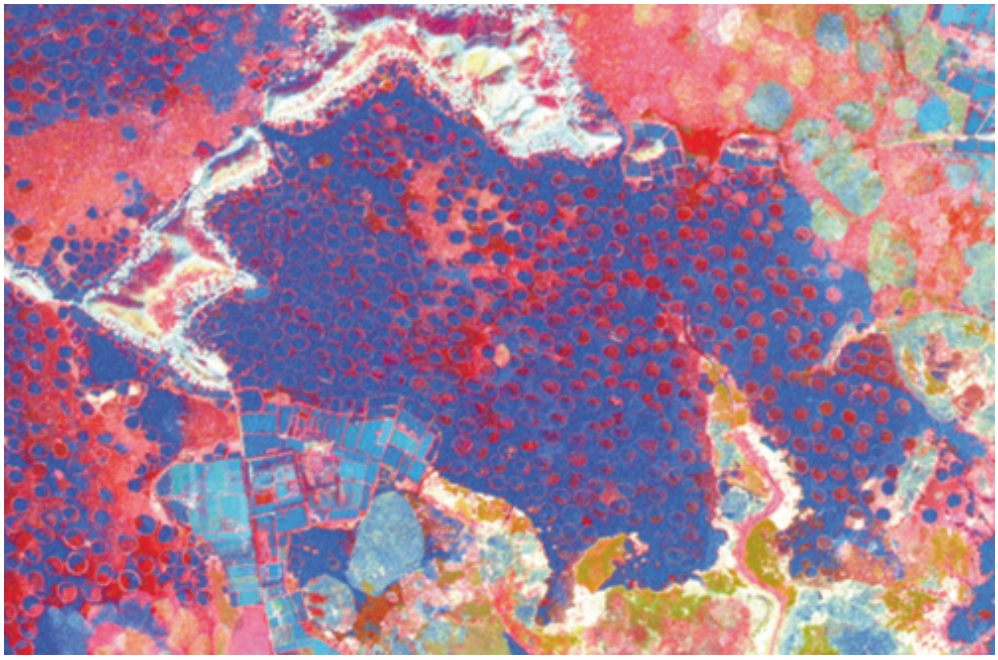
Concluding note

While many of the applications described are operational, some are in the pilot study phase (for example, conservation of heritage sites). Space technology can only offer tools but how those tools are used depends on those in charge of governance and the end users. Scientists and engineers can refine their tools based on feedback from the users. Continuous interaction between these three groups (the scientists, the administrators and the user community) is essential for full utilisation of the potential of space technology.

★★★



The Trans-Himalayan region, north of the Indus, forming India's frontier with Afghanistan and China in the northwest of Kashmir, is the Great Karakoram, a region of lofty peaks and vast glaciers. Some of the famous peaks are Mt K2 (8611 m), Hidden Peak (8068 m) and Broad Peak (8035 m), while the longest glacier is the Siachen Glacier of the Nubra Valley. The Ladakh Plateau occupies the northeastern portion of Kashmir.



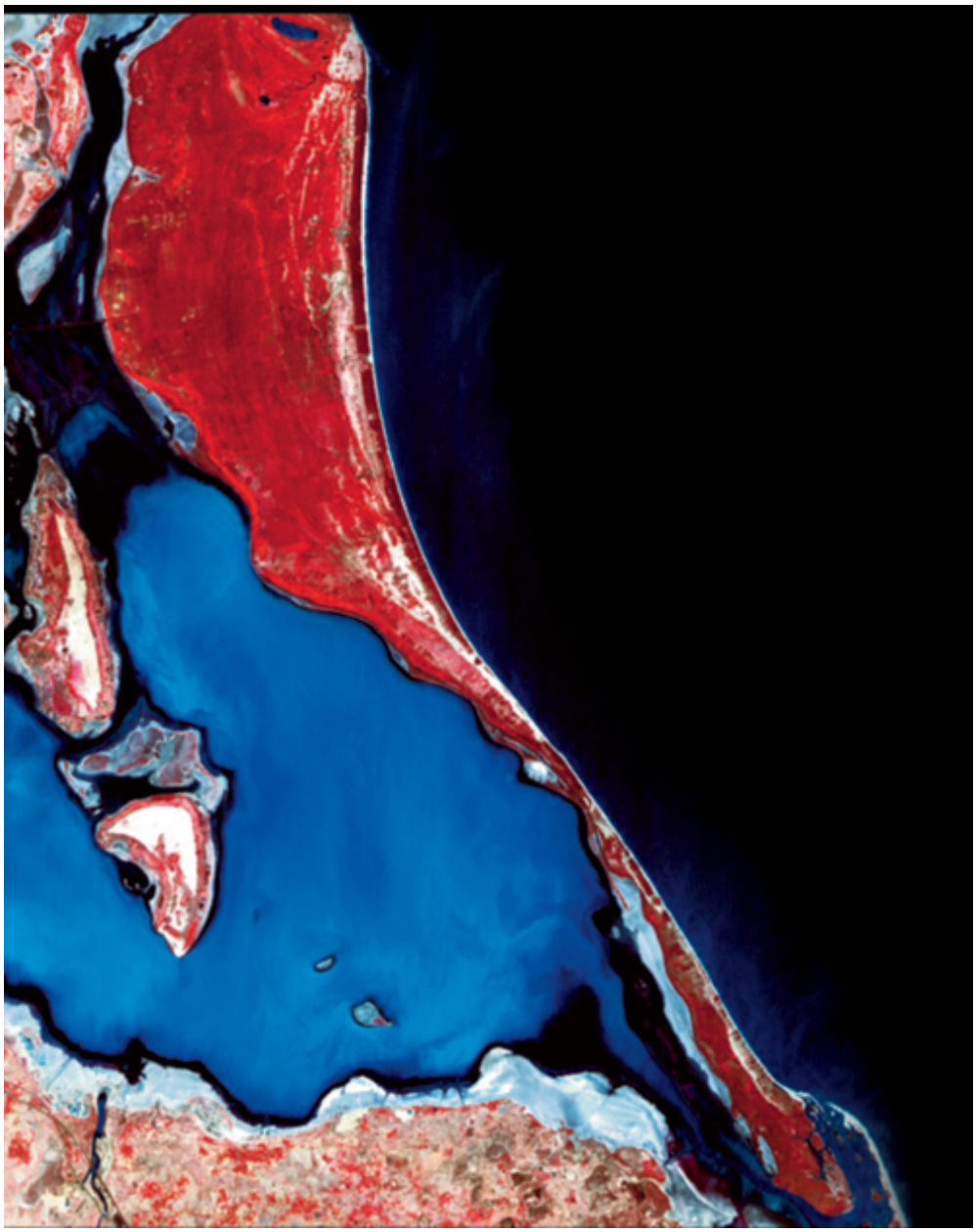
Athaphums, as seen by fusing images taken by the CARTOSAT-1 and LISS IV cameras. This technique is known as Kernel Linear Neighbourhood Propagation (KLNP). The result is a high-resolution colour image. KLNP is an example of an application of Artificial Intelligence.

Floating fish ponds, known as athaphums, in Loktak, Manipur, 2008. These circular artificial structures are used for rearing fish. Courtesy: Thounaojam Sanggai Leima.

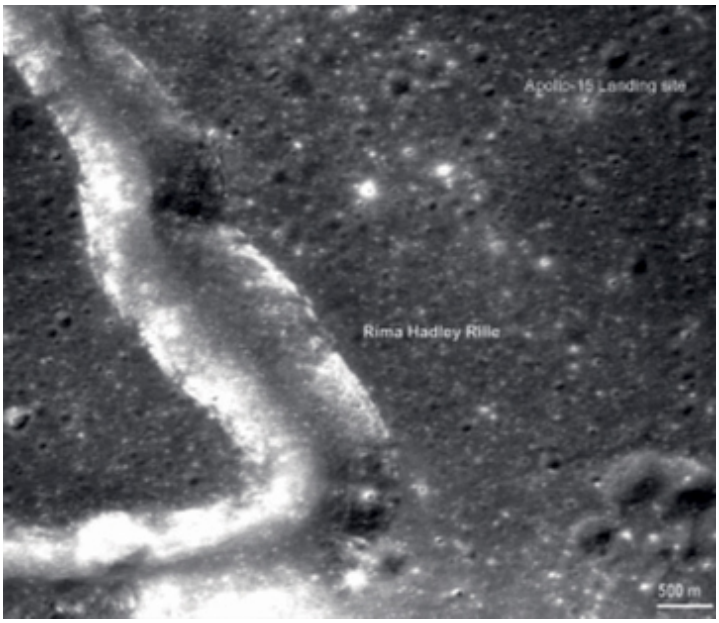
The Deccan Plateau, lying within the framework of the Satpura-Mahadeo-Maikal ranges, the Eastern Ghats and the Sahyadris, is slightly tilted towards the south-east. The heights vary from 900 m in the west to 300 m in the east. The Maharashtra Plateau in the north is formed of horizontal lava sheets, which have led to the formation of a typical Deccan Trap topography with hills, ridges and broad valleys. The Karnataka Plateau rises southwestwards and merges with the Nilgiris.

The Ganga Basin. The 2510-km-long Ganges, known as Ganga in India, rises in the Indian Himalayas and enters the Gangetic Plain northeast of Delhi. The Ganga river basin is India's largest, covering about 25% of the nation's area. The river Yamuna is the largest tributary of the Ganga, with a total length of around 1370 km. Its source is in Yamunotri in the Himalayas. The Ganga joins the Yamuna at Allahabad (now Prayagraj). The main branch of the Ganga flows through Bangladesh to the Bay of Bengal, while a second branch meets the Bay in India, south of Kolkata.

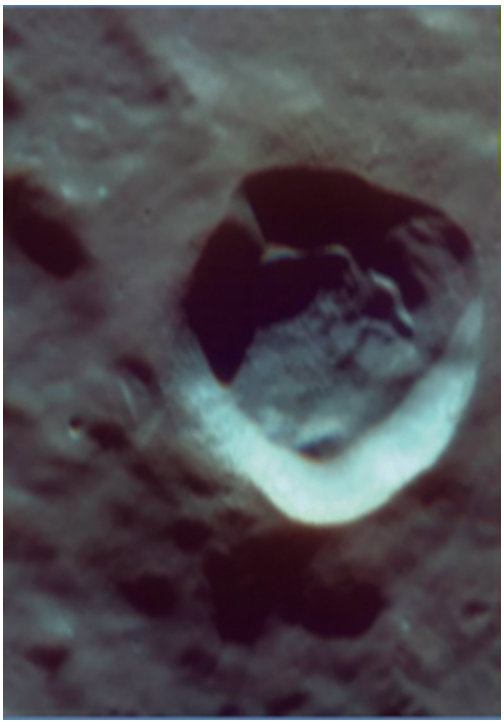
Pulicat Lake is the second largest brackish water eco-system on the east coast of India, 160 km north of Chennai city. A spectacular landmark from space, the lagoon covers an area of 1200 sq km, and is separated from the sea by Sriharikota island. It is fed by three rivers and many other canals and water outlets. Two medium-sized and a few tiny islands are situated in the lake. The mouth of the lake is a narrow channel of 200 m, with an average depth of about 1 m. Historically speaking, Pulicat Lake has been a gateway for several foreigners landing on Indian shores – the Arabs in the 14th century, followed by the Dutch and the British in the 16th and 17th centuries. Pulicat is endowed with diverse natural resources and aquatic and terrestrial fauna and flora. A fishing ground for thousands of native fishing folk, the lake is also a sanctuary for migratory birds, a paradise for bird watchers and a tourist destination. Sriharikota island is where the Satish Dhawan Space Centre (SDSC-SHAR) is located.



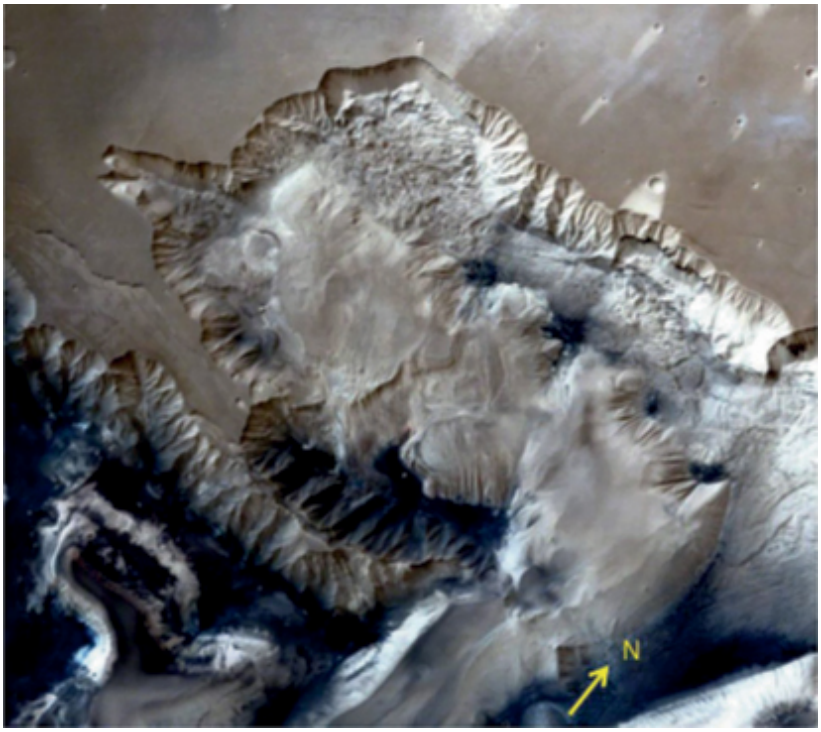
In the arms of the Arabian Sea is the commercial and financial hub of India, the city of Mumbai. The capital of Maharashtra, Mumbai (or Bombay) owes its name to the stone goddess Mumbadevi, and was once a cluster of seven islands, which have been bound together by reclamations to form this city. Spread over 440 sq km, the city is crisscrossed by a network of local trains, which connect the length and breadth of the city, carrying over 6 million commuters every day! Mumbai is amongst the best natural deep water harbours in western India, and hence, it has long been the principal gateway of India. Over the years, it has played a dominant role in developing the country's trade and commerce.



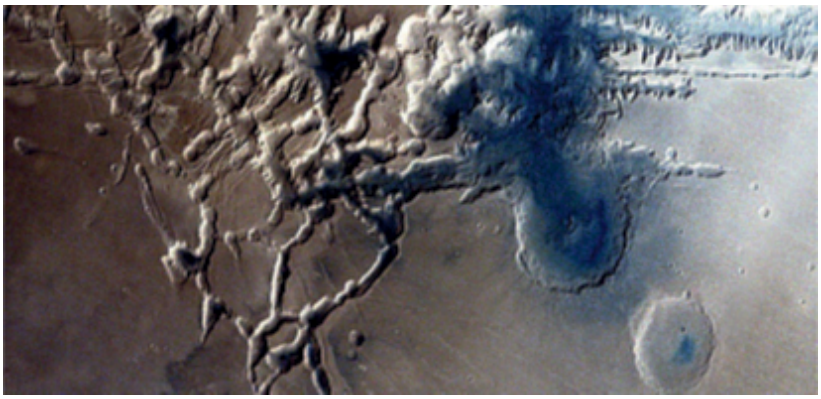
Chandrayaan-1 image of part of the Rima Hadley sinuous rille, located southwest of the Apollo-15 landing site.



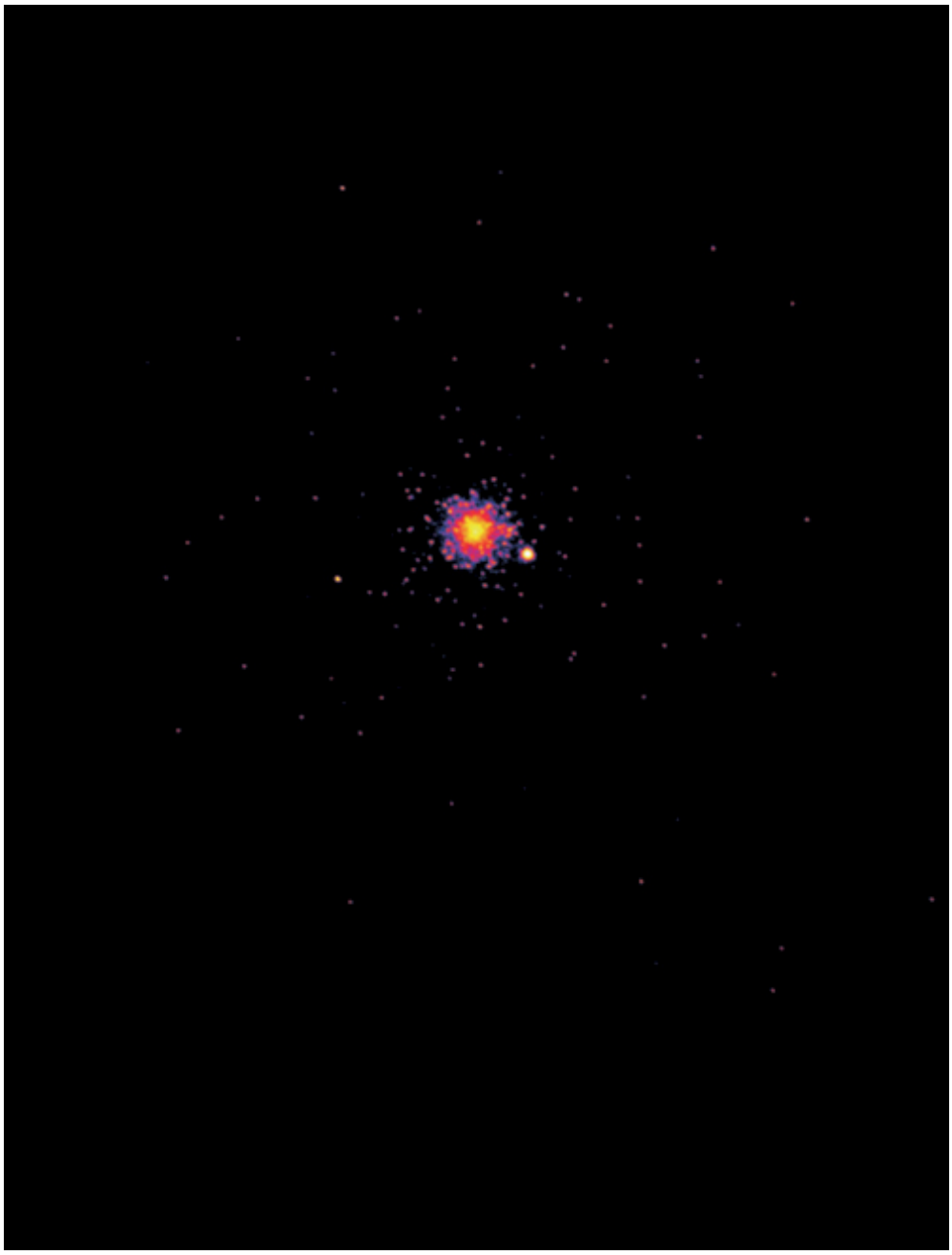
Lemaitre Crater, as seen by the Hyper Spectral Imager of Chandrayaan-1.

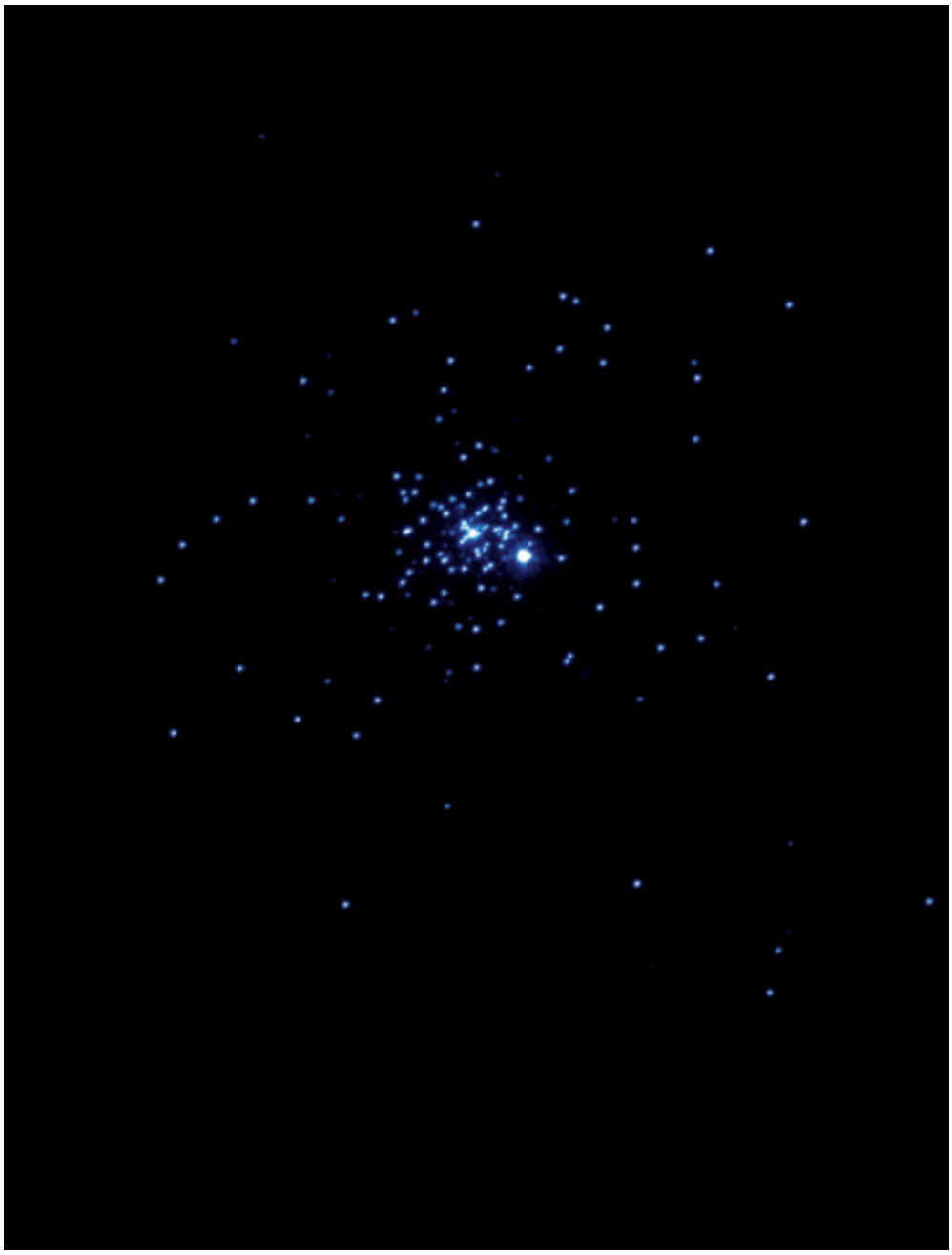


Mangalyaan image. A 3D view of the Ophir Chasma canyon, captured by MOM.

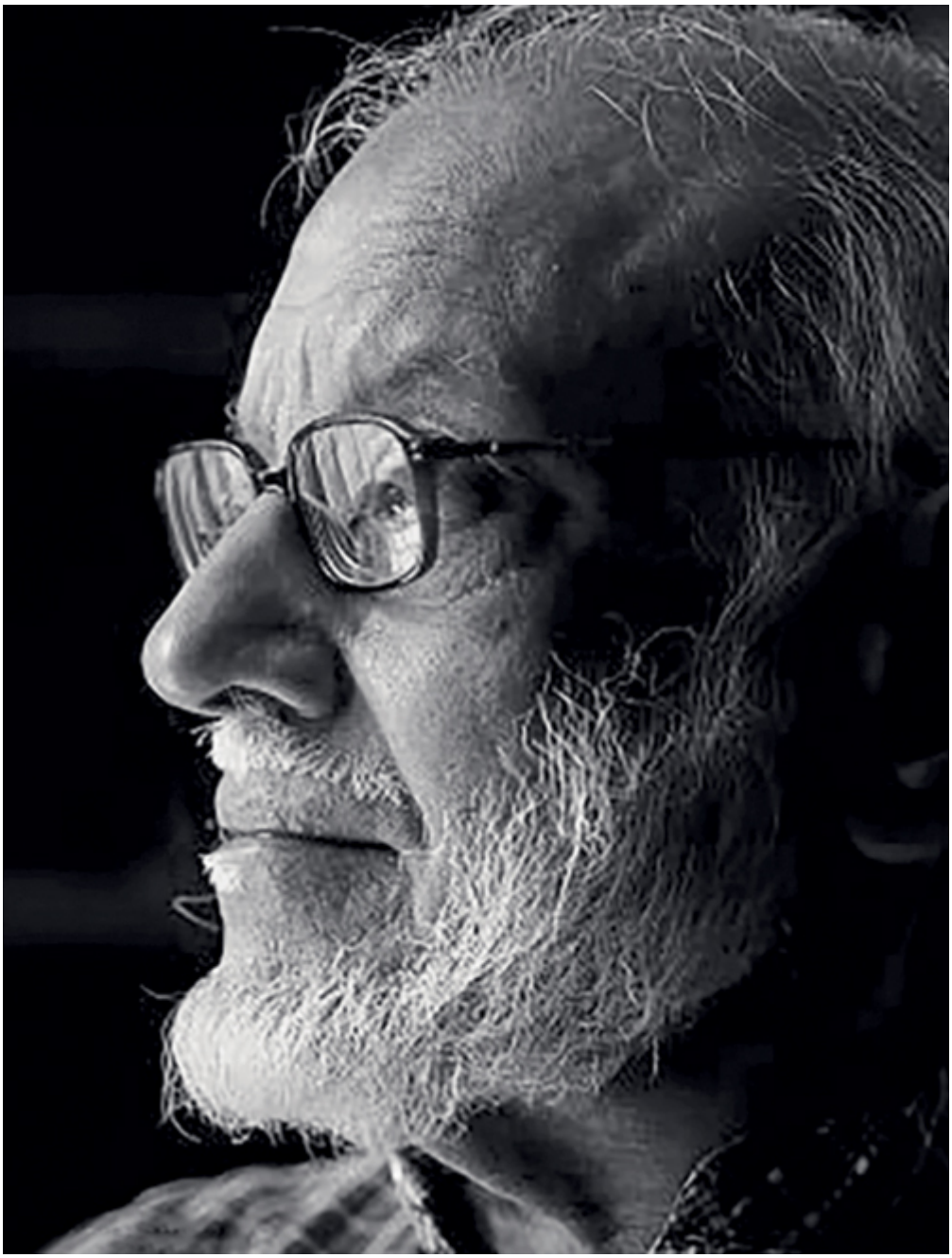


Mangalyaan image. Complex intersecting valleys or ridges on the Mars surface are known as Noctis Labyrinthus.





NGC 1851: Two star families in one globular cluster. Near-UV (left) and far-UV (right) images of the globular cluster, NGC 1851, taken by UVIT on-board ASTROSAT.



MGK Menon

Of People and Places

Introduction

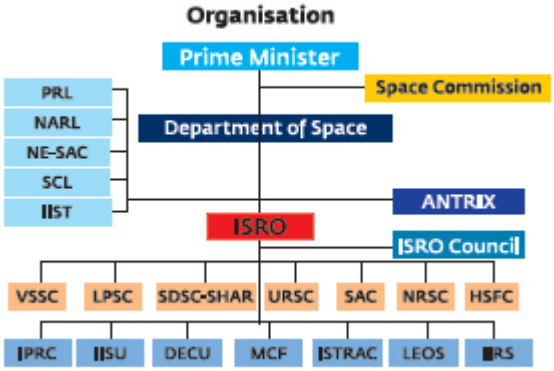
The two most valuable assets of the Indian space programme are: (1) the pool of talented and committed professionals and (2) laboratories and facilities which enable these professionals to carry out R&D at the cutting edge of space technology. Equally important is how the space programme is organised. We owe this 'organisational structure' to Satish Dhawan, who created the Department of Space and brought ISRO under it. (See Chapter 2: The Dhawan Era).

On the next two pages, we show the locations of the laboratories, facilities and offices of our space programme, along with the organisational chart and the latest Budget Profile. They are self-explanatory.

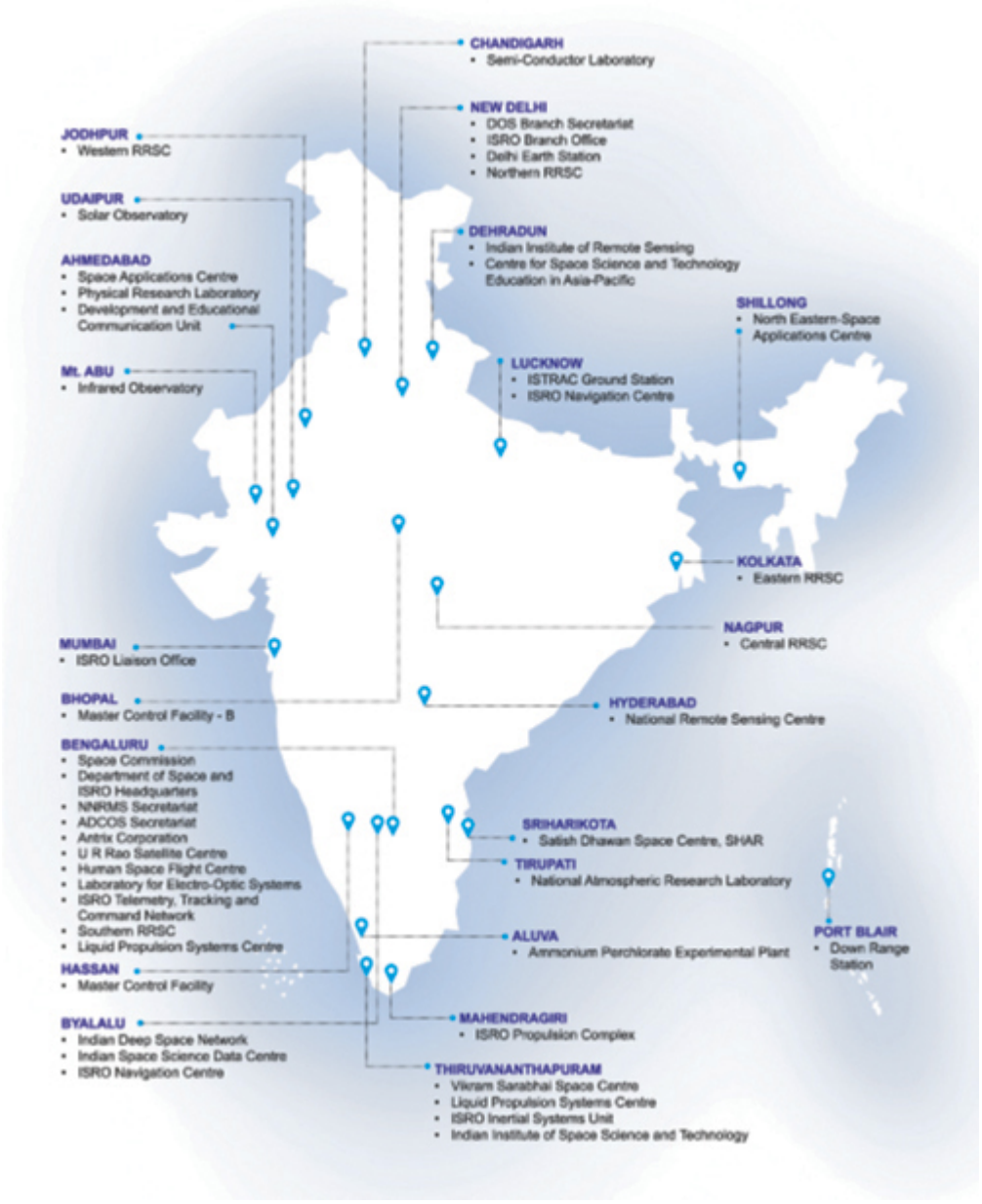
On 3 June 1972, President VV Giri appointed Prime Minister Indira Gandhi as Minister of Space. That tradition of space coming directly under the Prime Minister continues. Another tradition that continues is that the same technical person holds all three positions: Chairman, Space Commision; Secretary, Department of Space (DOS); and Chairman, ISRO. This arrangement ensures harmony between the nation's space policies (the Commission), the R&D programmes (ISRO) and the budgetary provisions (DOS).

The sanctioned human resource strength of DOS as on 1 March 2015 was 16,902, of which 12,300 are in the scientific and technical categories and 4602 are in the administrative categories.

We do not intend to describe what is done in each of these places; rather, we group them together depending on their main functions.



PRL: Physical Research Laboratory, **NARL:** National Atmospheric Research Laboratory, **NE-SAC:** North Eastern-Space Applications Centre, **SCL:** Semi Conductor Laboratory, **IIST:** Indian Institute of Space Science and Technology, **ISRO:** Indian Space Research Organisation, **Antrix:** Antrix Corporation Limited, **VSSC:** Vikram Sarabhai Space Centre, **LPSC:** Liquid Propulsion Systems Centre, **SDSC:** Satish Dhawan Space Centre, **URSC:** UR Rao Satellite Centre, **SAC:** Space Applications Centre, **NRSC:** National Remote Sensing Centre, **HSFC:** Humans Space Flight Centre, **IPRC:** ISRO Propulsion Complex, **IISU:** ISRO Inertial Systems Unit, **DECU:** Development and Educational Communication Unit, **MCF:** Master Control Facility, **ISTRAC:** ISRO Telemetry, Tracking and Command Network, **LEOS:** Laboratory for Electro-Optics Systems, **IIRS:** Indian Institute of Remote Sensing



Map of India showing the various workplaces of DOS and ISRO.

An external view of the Mission Control Centre at Satish Dhawan Space Centre, Sriharikota (SDSC-SHAR).

Inside view of the Mission Control Centre in SDSC-SHAR.

ISRO

We first deal with the laboratories under ISRO. Any useful space mission comprises four parts: (1) the rocket (that is, the launch vehicle), (2) the satellite (or the space probe) and its payload, (3) the ground network of stations that tracks and monitors the rocket and the satellite; it also commands the satellite and (4) the facilities on the ground that launch the rockets and those that receive and process the data sent down by the satellites or probes. Depending on the type of data transmitted, the processed information is disseminated to the concerned users.

All work related to the design, development and testing of rocket systems is done at the Vikram Sarabhai Space Centre (VSSC), Liquid Propulsion Systems Centre (LPSC), ISRO Propulsion Complex (IPRC) and ISRO Inertial Systems Unit (IISU). VSSC also supports the Space Physics Laboratary (SPL) whose scientists study the environments of the Earth and other planets.

All work related to the design, development and testing of satellites (and spacecraft) and their payloads is done at ISRO Satellite Centre (ISAC), now known as UR Rao Satellite Centre (URSC), Space Applications Centre (SAC) and IISU and LEOS (Laboratory for Electro-Optics Systems).

The rocket and the satellite are assembled together and then launched from Satish Dhawan Space Centre on Sriharikota island (SDSC-SHAR).

Once the rocket with the satellite leaves the ground, it is tracked and monitored by the ISRO Telemetry, Tracking and Command network (ISTRAC), which has stations both in India and abroad. Satellites in geostationary orbits (mainly, communication and navigation satellites) are tracked, monitored and commanded by the Master Control Facility (MCF), which has stations at Hassan (Karnataka) and Bhopal (Madhya Pradesh).

Images from all remote sensing satellites are received and processed mainly by the National Remote Sensing Centre (NRSC). Almost all satellite-based information, whether it is related to remote sensing or weather or natural disasters, is made available to the concerned agencies and to the public in near-real-time through ISRO's own geoportal, known as Bhuvan.

The Development and Educational Unit (DECU) is concerned with socio-economic research with a view to evaluating societal applications of our space programme.

The Indian Institute of Remote Sensing (IIRS) is an education and training centre dealing with remote sensing and geo-informatics and their applications.

Inside the PCMC (Precision Coherent Monopulse C-Band) Radar Control Room at SDSC-SHAR.

Weather balloons are released to measure winds before a launch. A view from SDSC, Sriharikota.

Department of Space (DOS)

This is the Government Department under which ISRO and other entities shown in the Organisation Chart operate. Thus, DOS ensures that all those entities operate smoothly within the framework of the departmental rules and regulations.

We now briefly describe the main objectives of the entities that come under DOS.

As described in Chapter 1, the Physical Research Laboratory (PRL) is the cradle of the nation's space programme. Today, it is a premier institute in the country in which basic research is carried out in Astronomy & Astrophysics, Solar Physics, Planetary Exploration, Space & Atmospheric Sciences, Geo-sciences, Atomic, Molecular & Optical Physics and Astro-chemistry.

The National Atmospheric Research Laboratory (NARL) is a national facility supported by DOS. Its main objective is to develop the capability to predict how the atmosphere behaves through observations and modelling.

The North Eastern-Space Applications Centre (NE-SAC) provides developmental support to the northeastern region of the country using space science and technology.

Semi-Conductor Laboratory (SCL), an autonomous body under DOS, is engaged in creating a strong microelectronics base in the country.

The Indian Institute of Space Science and Technology (IIST) is Asia's first Space University. It was established in 2007 with a view to offering quality education in space science and technology to meet the human resource demands of the national space programme.

Antrix Corporation Limited is a company wholly owned by the Government of India under the administrative control of DOS. It is basically the marketing arm of ISRO that promotes commercial utilisation of space products, including consultancy services and transfer of technologies developed by ISRO.

Photo gallery

What follows is a collection of photographs of some of the places where ISRO has built infrastructure and of people, including visitors, to those places. We have used no particular criterion in selecting these photographs. This collection may be described as eclectic in its spirit. We hope the reader enjoys looking at these pictures which speak for themselves!

★ ★ ★

ISRO's 32-metre-diameter antenna dish at Bylalu, near Bangalore; used for Deep Space missions.

A visit of the Chief Minister of Karnataka to the Deep Space Network, Bylalu. From left: RG Nadadur, G Madhavan Nair, Yediyurappa's daughter, BS Yediyurappa (Chief Minister), SK Shivakumar, SV Ranganath and GR Hathwar (others not identified).

ISRO has a tracking station at Lapan, Indonesia.

Seaborne tracking support for Mangalyaan.

An inside view of the Mission Operation Complex (MOX) at Peenya, Bangalore.

Prime Minister Narendra Modi congratulating ISRO after the successful Mangalyaan orbiter insertion into the Mars orbit (24 September 2014).

Antenna system at Master Control Facility (MCF), Hassan.

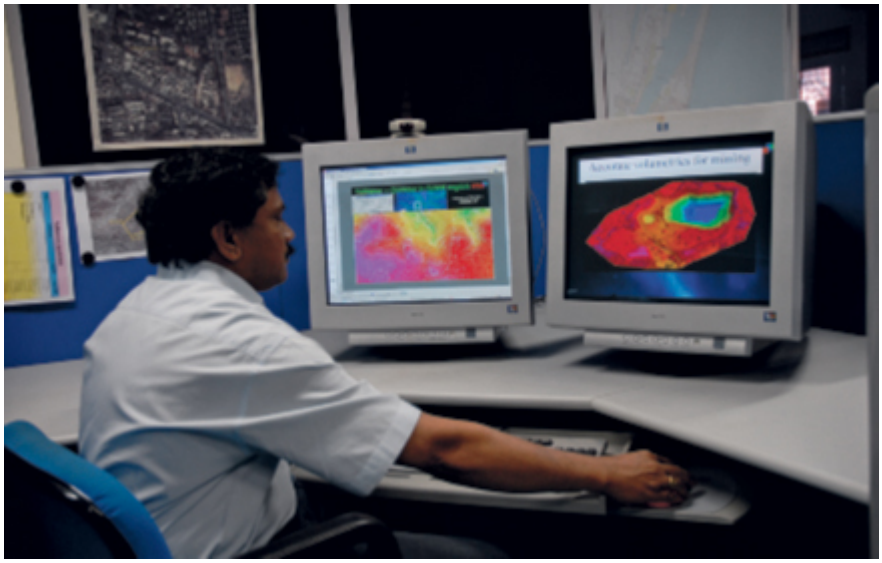
A view of the Earth station at MCF, Hassan.

Antenna set up at Shadnagar, near Hyderabad, to receive Earth resources data directly from the Landsat series of satellites launched by NASA, during 1977–78.

An inside view of MCF, Bhopal.

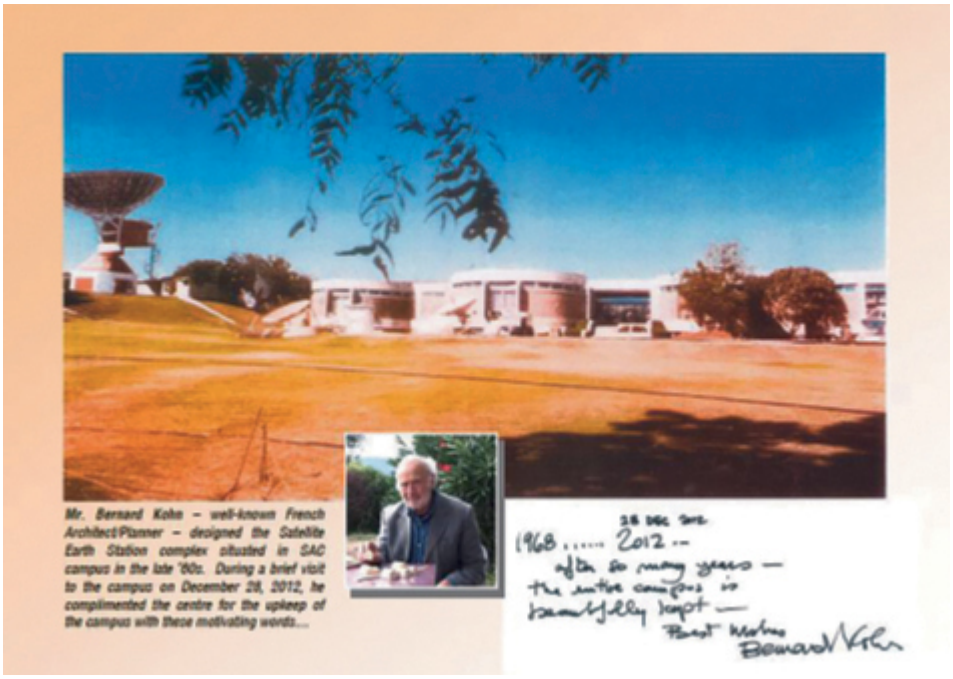
National Remote Sensing Centre (NRSC) has an aircraft for aerial survey.

NRSC signs agreement with Andhra Pradesh. From left: YVN Krishanmurthy, AS Kiran Kumar (Chairman, ISRO) and Chandrababu Naidu (Chief Minister of AP).



Photogrammetric data processing being done at NRSC.

A visit to the Russian Scientific Station "Novo" in Antarctica by the NRSC-ISRO team. The 32nd Indian Antarctica Expedition (February 2013). From left: Deepika Roy, Padmavathy CS, K Sudhakar and AVV Prasad.


Mr. Bernard Kohn – well-known French Architect/Planner – designed the Satellite Earth Station complex situated in SAC campus in the late '60s. During a brief visit to the campus on December 28, 2012, he complimented the centre for the upkeep of the campus with these motivating words....
1968 ..... 2012 --
after so many years —
the entire campus is
beautifully kept —
Bernard Kohn

Experimental Satellite Communication Earth Station (ESCES) in Ahmedabad was built during the 1960s. Its architect, Bernard Kohn, visited Ahmedabad Earth Station in 2012.

A more recent view of Ahmedabad Earth Station.

The new entrance to Vikram Sarabhai Space Centre, Thiruvananthapuram, with the Main Building on the left.

Night view of the Main Building.

Udaipur solar observatory.

Liquid Propulsion Systems Centre (LPSC), Bangalore.

A view of UR Rao Satellite Centre, Bangalore.

A view of North Eastern-Space Applications Centre, Meghalaya.

Liquid Propulsion Systems Centre (LPSC), Valiamala, Thiruvananthapuram.

Semi-Conductor Laboratory, Chandigarh.

ISRO Headquarters, Antariksha Bhavan, Bangalore.

The Gandhi Peace Prize for 2014 was awarded to the Indian Space Research Organisation.

Chairman, ISRO, AS Kiran Kumar, receiving the Gandhi Peace Prize from President Pranab Mukherjee.

An exhibition organised by Antrix Corporation (the commercial wing of DOS).

PP Mohanlal hoisting the National Flag on Republic Day at IISU.

Development and Educational Communication Unit, Ahmedabad.

Laboratory for Electro-Optics Systems.

Indian Institute of Remote Sensing, Dehradun.

Physical Research Laboratory, Ahmedabad.

Indian Institute of Space Science and Technology, Valiamala, Thiruvananthapuram.

Yagi Antenna Array at National Atmospheric Research Laboratory, Gadanki, Andhra Pradesh.

The new entrance to SDSC-SHAR being inaugurated by K Sivan, Chairman, ISRO. Also seen are PLN Srinivasa Rao, TS Raghuraman, JV Raja Reddy, R Venkatraman, V Ranganathan, P Kunhikrishnan, T Gunasekaran and Kumbakarnan.

Celebrating the 50th launch from Sriharikota. From right: MYS Prasad, MC Dathan, M Annamalai, K Narayana, S Vasantha, P Kunhikrishnan, AS Kiran Kumar, BN Suresh, S Srinivasavan, K Sivan, JV Raja Reddy and T Subba Reddy.

S Somanath, hoisting the tricolour at LPSC, Valiamala, Thiruvananthapuram..

Charles F Bolden, former Administrator, NASA, speaking to the SDSC-SHAR community.

Rockets excite young minds! An ISRO exhibition at Chandigarh.

APJ Abdul Kalam releasing the book, A Brief History of Rocketry in ISRO, written by PV Manoranjan Rao (on Kalam's right) and P Radhakrishnan at the first convocation of IIST, 2012.

A view of the canteen at ISAC (now URSC).

A view of an administrative office at DOS.

President Fakhruddin Ali Ahmed and his wife visiting VSSC. On the President's right is Satish Dhawan. Extreme right (with tie) is Brahm Prakash.

VP Balagangadharan (centre) distributing prizes to winners of competitions held during the space week celebration 2010 at VSSC.

Prime Minister Manmohan Singh (turban) visiting an ISRO Centre. Also seen are RR Navalgund (extreme right) and K Radhakrishnan.

President Giani Zail Singh visiting VSSC. On his left is Governor Ramachandran and VR Gowariker. On the extreme left: Chief Minister of Kerala, K Karunakaran.

Prime Minister Atal Bihari Vajpayee (traditional dress with a shawl) at Sriharikota. Also seen from left: S Vasantha, N Vedachalam (National Security Advisor), Brajesh Mishra, Pramod Mahajan, K Kasturirangan, S Ramakrishnan, C Rangarajan, S Srinivasan, Chandrababu Naidu, S Krishnamurthy, Vasundhara Raje, RN Bhattacharya and Rajaram Nagappa.

Prime Minister Manmohan Singh (turban) at Sriharikota. Also seen are V Narayanasamy, MC Dathan, K Radhakrishnan. P Kunhikrishnan and Seshagiri Rao.

APJ Abdul Kalam at Mission Operation Complex, Peenya, Bangalore. Celebrating the Moon impact probe crash-landing on the Moon's surface. Also seen are S Ramakrishnan, UR Rao, G Madhavan Nair, SK Shivakumar, TK Alex, K Radhakrishnan and Kishore Nath.

Michael Griffin, Administrator of NASA, presenting a model of a space shuttle to G Madhavan Nair, Chairman, ISRO. K Sankara is on the extreme right.

BN Suresh (centre) explaining the launch sequence to Prime Minister Narendra Modi (left) and Venkaiah Naidu (later Vice-President of India).

SPL scientists on-board 'Sagar-Kanya', releasing a weather balloon. From right: Mushin, Aryasree, Sunilkumar, Suresh Babu amd Sathish Chandra. The other two are crew members of 'Sagar-Kanya'.

Prime Minister AB Vajpayee (sixth from left) seen against the background of the fully integrated INSAT-2E. Also seen from left: TL Danabalan, AD Dharma, PS Goel, K Kasturirangan, Prime Minister AB Vajpayee, Ramakrishna Hegde, Khursheed Alam Khan, A Bhaskara Narayana and VR Katti.

Prime Minister PV Narasimha Rao (white traditional Andhra dress) visiting Sriharikota. Also seen are MC Uttam, UR Rao, Arjun Singh and SC Gupta.

Prime Minister Rajiv Gandhi (orange hardhat) in Sriharikota. UR Rao is seen on the PM's left.

Prime Minister Chandrasekhar visiting the Satellite Centre. Also seen are K Kasturirangan and UR Rao (extreme right).

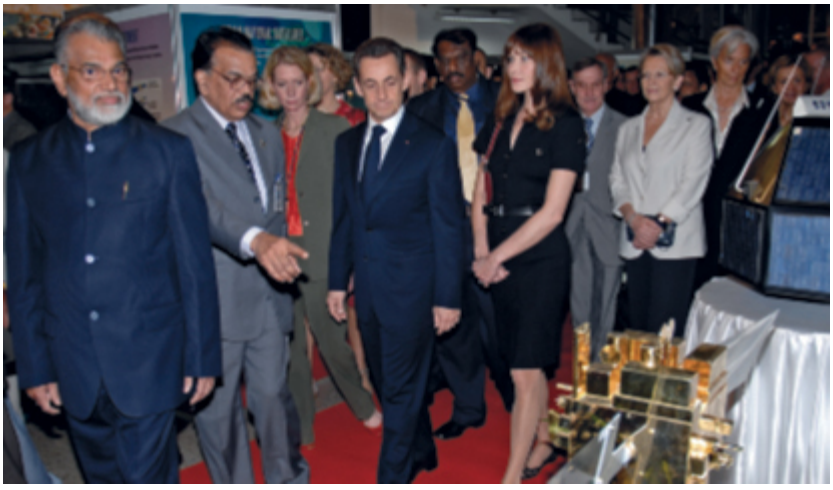
The Indian team with their Russian counterparts photographed in front of Anthariksha Nivas, Shriharikota (SDSC-SHAR). This was when Russia was contracted to supply the cryogenic stage for the GSLV.

Colourfully dressed Member of Parliament, Ashwini Kumar Choubey, visiting NRSC. To his left is YVN Krishnamurthy.

Picture taken at VSSC on the occasion of the unveiling of the bust of Sarabhai in front of the main building. Standing (from left): AC Bahl, DS Rane, BC Pillai, Abdul Majeed, not identified), Sreedharan Dhas, EVS Namboothiri, BN Suresh, V Sundara Ramaiah, K Narayana, (not identified), RV Perumal, PS Goel, N Vedachalam, Sudhakar Rao, Yash Pal, (not identified), (not identified), PS Veeraraghavan, D Narayana Moorthi, S Ramakrishnan, RAD Pillai, KK Athithan, (not identified), YS Rajan, Prabhakaran and Kathikeya Sarabhai. Sitting (from left): MK Mukarjee, SC Gupta, AE Muthunayagam, K Kasturirangan, Mrs Menon, MGK Menon, Mrinalini Sarabhai, APJ Abdul Kalam, EV Chitnis, G Madhavan Nair, TN Seshan and Mallika Sarabhai.

President APJ Abdul Kalam seen with his former ISRO colleagues. from left: GK Kuruvila, V Gnanagandhi, MYS Prasad (partly seen), G Madhavan Nair, G Ravindranath, V Adimurthy, Balakrishnan, N Narayana Moorthy, Seshagiri Rao and G Viswanathan.

Nobel Laureate S Chandrasekhar being received at VSSC by Director, SC Gupta. Also seen are PV Manoranjan Rao (extreme left), Mrs. Mathews and Rajagopal.



French President Nicolas Sarkozy and his wife visited ISAC (now URSC) in 2010. TK Alex (second from left) is seen explaining a model to the President. Also seen is K Radhakrishnan (extreme left).

Releasing the Mars Atlas; from left: YVN Krishnamurthy, M Annadurai, AS Kiran Kumar, Tapan Misra and DP Karnik.

PG Divakar addressing a workshop organised by the United Nations Office for Outer Space Affairs.

Shankaracharya of Puri with his disciples visiting SAC, Ahmedabad. Seen on his right are AS Kiran Kumar (blue shirt) and Tapan Misra (with cap).

Celebrating Bhuvan. Sitting (from left): VC Naidu, Subrat Kumar Acharya, Leonard Prakash, Naresh Kumar, PM Bala, Arulraj, Syed Shadab, Naresh N, SH Rao, Mohan, Rajani B, Srikanth and Sonal Aggarwal. Standing first row (from left): CC Reddy, Aditya Kumar Singh, Tharak, vv Raghu, PG Diwakar, A Thirunavukkarasu, VK Dadhwal, K Radhakrishnan, V jayaraman, AS Manjunath , Rajendra Kumar, Harish Karnatak and Rama Devi. Standing second row (from left): J Ramanamurthy, Nilanjan Routh, (not identified), YVN Krishnamurthy, P Aravindakumar, Ravi and Bikshamiah.

ADRIN Management Council; from left: SK Patra, V Raghu Venkataraman, S Venkataraman and U Gopalakrishna.

VSSC Management Council. From left: ES Padmakumar, SR Biju, A Rajarajan, J Jayaprakash, M Narayanan Namboothiripad, CR Thomas, M Mohan, Roy M Cherian, V Kishorenath, S Somanath, Biju Jacob, G Ayyappan, B Valsa, NP Giri, A Shooja, V Ashok, Radhika Ramachandran, Sharad Chandra Sharma and G Levin.

IPRC Management Council (ICMC); from left: SK Govindarajan, K Alaguvelu, T Mookiah, J Asir Packiaraj, L Louis Sam Titus and M Prasannan.

IISU Management Council. Sitting (from left): KS Mani, Sam Dayala Dev, CC Joseph and A Abdul Shukorr. Standing (from left): K Anilkumar, S Sivasubramony, Paul Pandian and S Hemachandran.

ISTRAC Management Council. From left: P Ekambaram, G Chandrasekhar, BN Ramakrishna, KG Srinidhi, R Srinvasan, VV Srinivasan, A Indra, Subhalakshmi Krishnamoorthy, V Brinda and BV Ashoka.

LEOS Council Members. From left: Ganesha Shanbhogue, J Srinivasa Rao, Kalpana Arvind, AS Laxmiprasad, LV Prasad, Elumalai and KV Sriram.

LPSC Management Council (LPMC). Sitting (from left): G Narayanan, KN Saraswathy, V Narayanan, D Gangadhar, R Muthukumar and MS Suresh. Standing (from left): B Gita, PC Jacob Panicker, S Sunilkumar, M Radhakrishnan, HS Venkatesh, A Manimaran, R Narayan and KM Arul Kumar.

MCF - Executive Council. From left: Moinuddin Sheriff, HD Ananda, Aravinda Prakash, SN Sathyanarayana, HP Shenoy, S Prem Kumar, K Ratnakara, MN Subramaniayan, GS Raju, Shreyala Ratnakara and Shelendra Kumar.

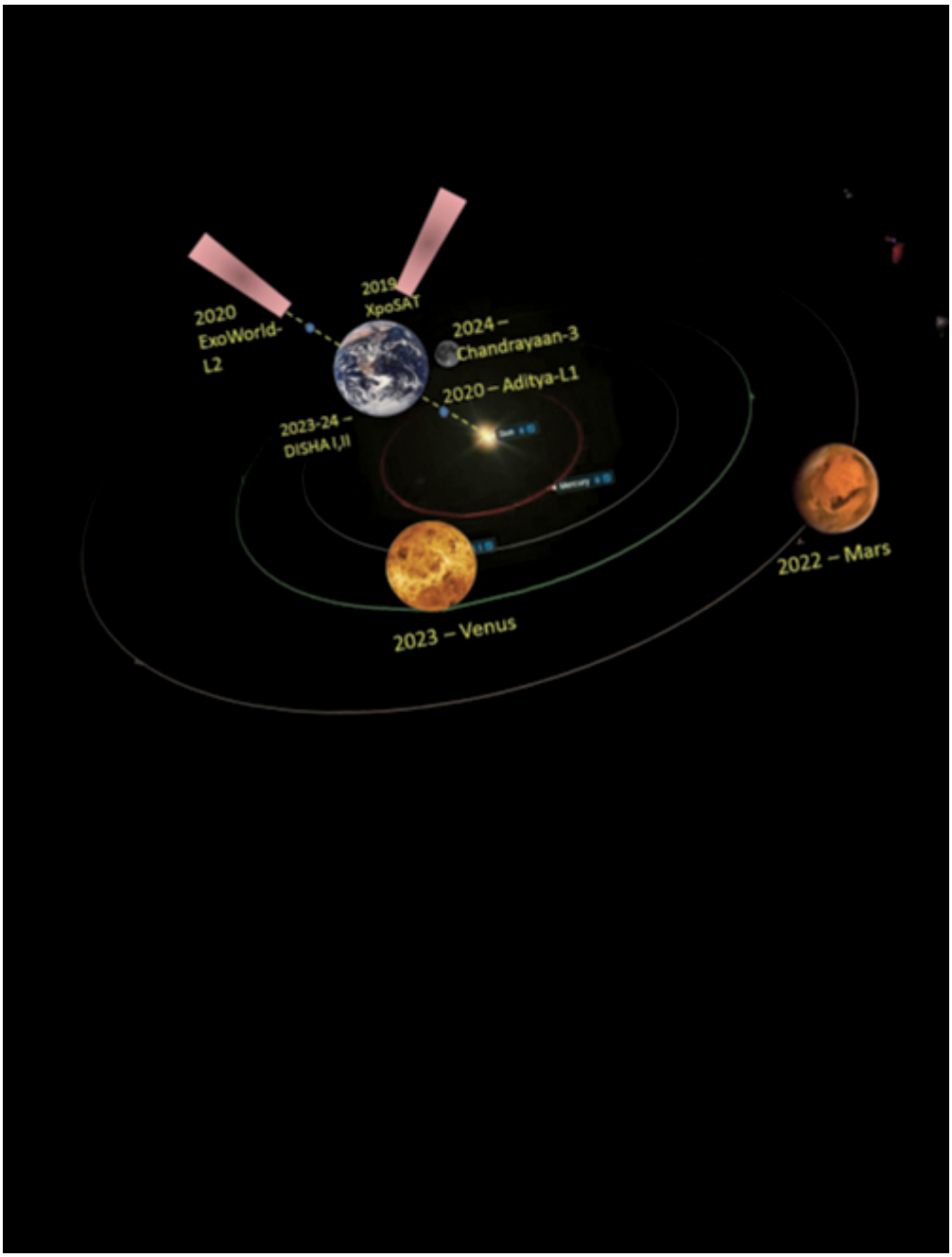
SAC Council Members. From left: KS Parikh, Raj Kumar, Apurba Bhattacharya, Debajyoti Dhar, Rajeev Jyoti, Virender Kumar, DK Das, Nilesh Desai, Piyush Verma, Ajay Kumar Lal, Hemen Kansara, Somya Sarkar, SN Satashia and MB Mahajan.

NRSC Management Council. From left: G Umadevi, MVR Seshasai, Vinod M Bothale, K Mruthyunjaya Reddi, Sanatanu Chowdhuri, V Bhanumurthy,

PVN Rao, Uday Raj, P Srinivasulu and Vibhas Singh Gupta.

SDSC Management Council; from left: KGK Moorthy, P Selvaraj, P Ponginan, V Ranganathan, S Pandian, MBN Moorthy, Gopi Krishna, Syed Hamed, KM Reddy and R Venkat Raman.

URSC Management Council. Sitting (from left): Sandhya Venugopal Sharma, S Venkateswara Sharma, K Sethuraman, AS Laxmi Prasad, P Kunhikrishnan, Anand Kumar Sharma, G Nagesh, R Rama Subramanian and N Valarmathi. Standing (from left): N Pattabhi Raman, Deviprasad Karnik, Subramanya Udupa, V Venkatesh, Pradeep Kumar Gupta, VK Hariharan, BS Kiran, PJVKS Prakasha Rao and M Sankaran.



Future: A Glimpse

The future plans of ISRO can be conveniently classified into three categories: imminent, near future and far future.

Imminent: Chandrayaan-1, launched in 2008 was a huge success. Its successor, the **Chandrayaan-2** spacecraft, is ready in all aspects. Its launch is imminent in the sense that ISRO may announce the date and time of the launch any day. Chandrayaan-2 is an advanced version of Chandrayaan-1. It comprises two modules: (1) Orbiter Craft (OC) and (2) Lander Craft (LC). The latter carries a Rover designed and developed by ISRO. As the name implies, the OC would orbit the Moon while the LC would gently place the Rover on the Moon's surface. The Rover is actually a robot that would move around the lunar surface and perform experiments designed by the scientists.

Near future: (1) Development of a **semi-cryo booster stage for GSLV Mk III** with an up-rated cryogenic stage. With this, the vehicle would be able to place a 5-tonne payload into Geosynchronous Transfer Orbit (GTO). (2) Development of Small Satellite Launch Vehicle (SSLV). This is an all-solid-propellant, three-stage rocket that can be assembled and launched within 3 to 5 days. (A rocket like GSLV Mk III takes several weeks). ISRO hopes to capture a significant part of the international market for small satellite launch services using SSLV. (3) **Gaganyaan,** the human space mission, is perhaps the most ambitious and complex mission ever undertaken by ISRO.

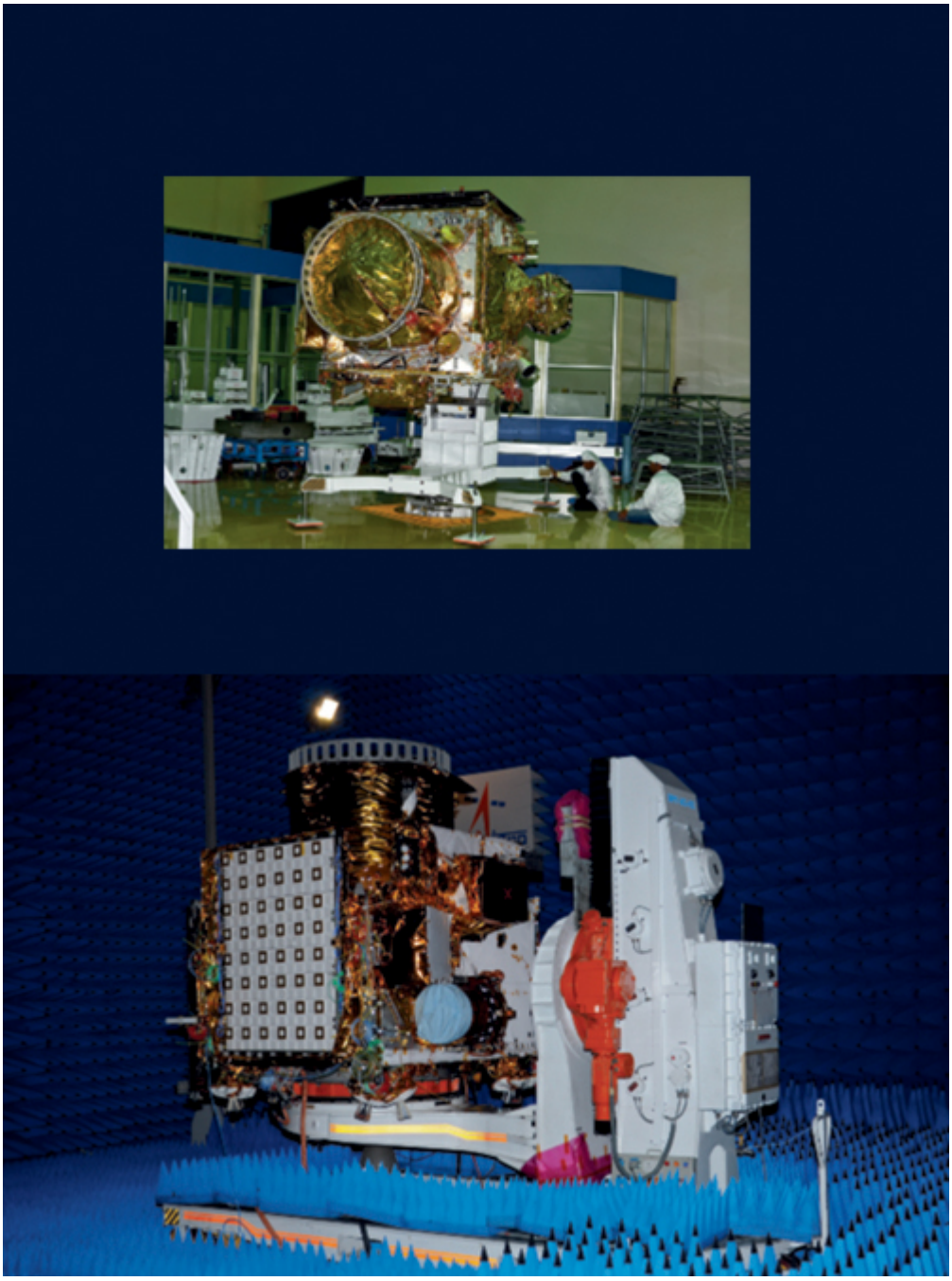
Far future: The long-term goals of ISRO include the development of modular, **recoverable and re-usable launch vehicles** which would be cost-effective. The goal is to enhance payload capacity to 5–15 tonnes in GTO. Towards this objective, ISRO has conducted some very basic experiments such as SCRAMJET demo and Recoverable Launch Vehicle Technology Demonstrator. Here, we are referring to the 2030s and beyond.

In satellite technology, the future points towards **all-electric communication satellites** which would replace the currently used chemical propulsion systems. This would enhance the payload capability considerably.

Space sciences: In the exploration of outer space, ISRO has plans for a very exciting future extending to the 2030s and beyond(see facing page).

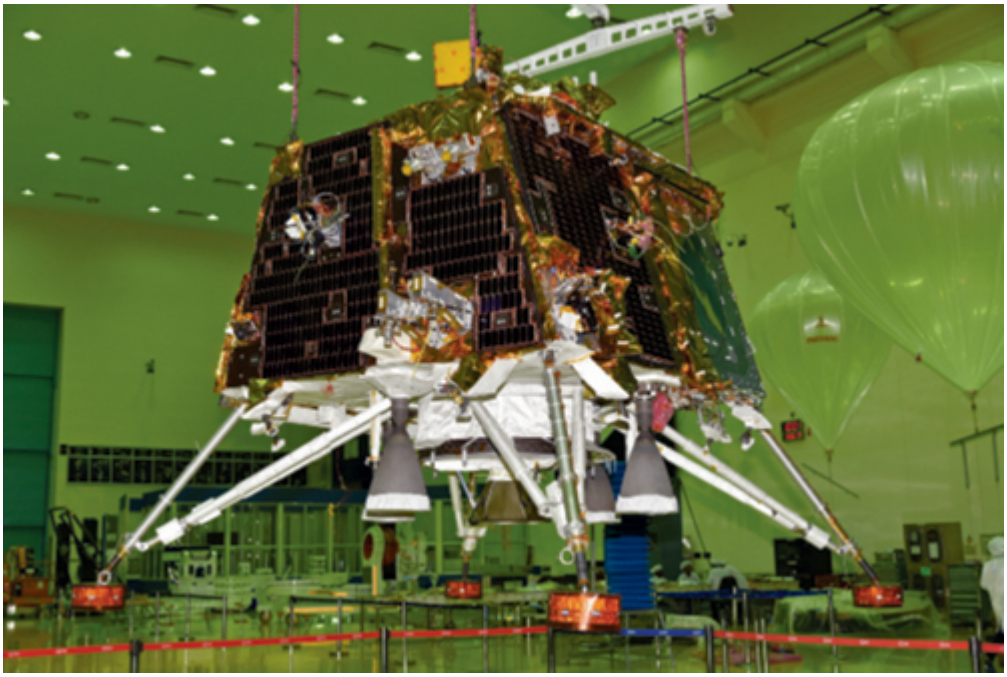
With established capability in Space Applications for societal development, the future strategy is to strengthen applications through the synergistic use of Earth observation, communication and navigation satellites, with specific focus on harnessing the benefits of space technology in the following broad areas:(i) Security of food, water, energy, health, shelter, infrastructure and information; (ii) Sustainable development; (iii) Disaster risk reduction and (iv) Governance-related issues.

★★★

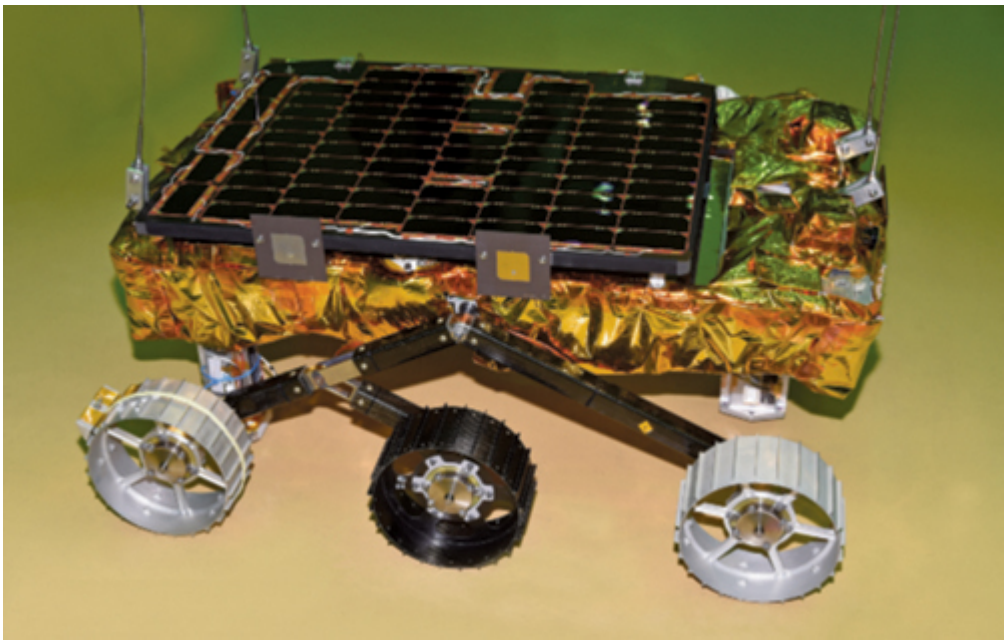


Chandrayaan-2 undergoing centre-of-gravity and moment-of-inertia measurement at URSC.

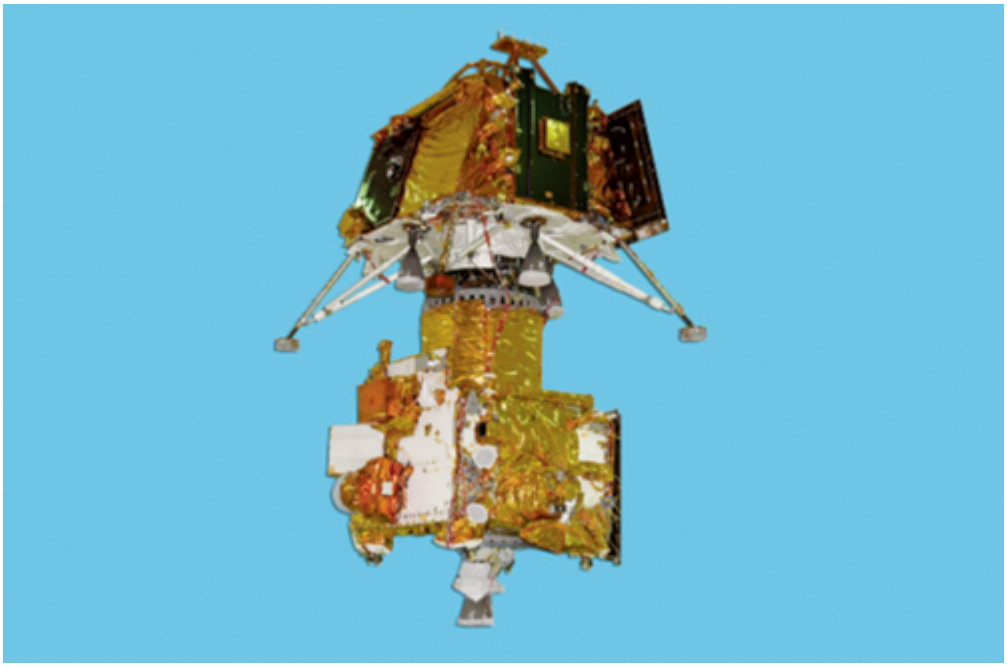
Chandrayaan-2 Orbiter undergoing EMI/EMC testing.



Chandrayaan-2 Lander, VIKRAM.

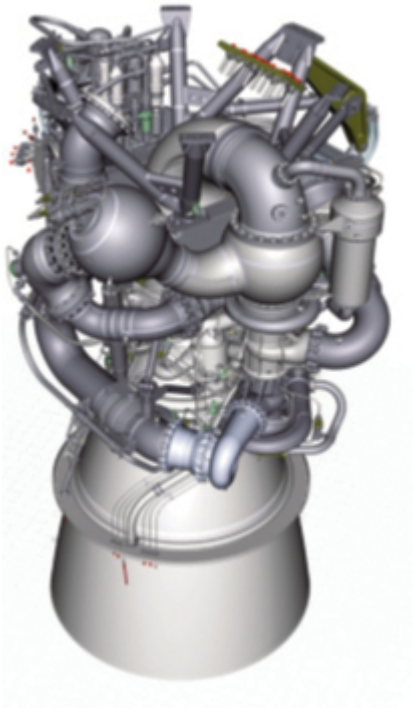


Chandrayaan-2 Rover, named PRAGYAN.

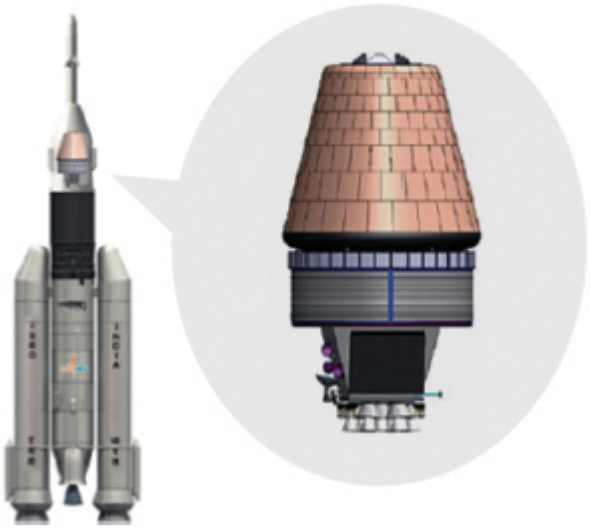


Chandrayaan-2 Integrated Module.

Small Satellite Launch Vehicle (SSLV) intends to be a strong contender in the growing market for commercial launch services to small satellite constellations. With a payload capability of 350 kg to SSPO, this all-solid propellant, three-stage launch vehicle is designed for easy assembly, integration and check-out operations in three days, thereby enabling quick response launch and low turnaround time between launches.



The successful qualification of a 2000-kN semi-cryogenic (LOX/kerosene) engine will enable the development of a booster stage that, when combined with an up-rated Cryogenic Upper Stage, will enhance the payload capability of GSLV Mk III to in excess of 5 tonnes to GTO. A clustered engine configuration will power the next generation of heavy-lift launch vehicles.

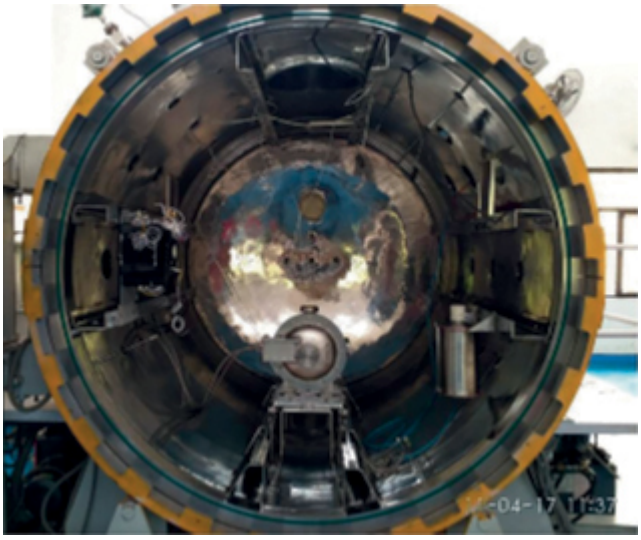


Gaganyaan, the Indian human spaceflight programme, is expected to generate tangible and intangible benefits through the stimulation of innovation in the country and aims to fulfil the aspirations of India as an established space-faring nation. This will also close any existing technological gaps while aligning with the global strategy of cooperative, inter-operable, affordable and low-risk human space exploration, ultimately leading to significant growth in scientific and technological capability for potential extra-terrestrial resource utilisation.

The Russian Ambassador in front of the Crew Module. From left: R Hutton, R Umamaheswaran, VR Lalithambika, K Sivan, Elena Kudasheva, Nikolay Kudashev, S Unnikrishnan Nair, Oleg Avdeev, Artem Baryshev, Yulia Golubkina and Vladimir Poluektov.

The Russian Ambassador looking at the Crew Escape System (CES) model.

The authors of this book with the Yuvika (VSSC Group-2019). VP Balagangadharan (extreme left), BN Suresh (fourth from left) and PV Manoranjan Rao (fifth from left).
Also seen are PV Venkitakrishnan (sixth from left) and M Shajahan (extreme right).

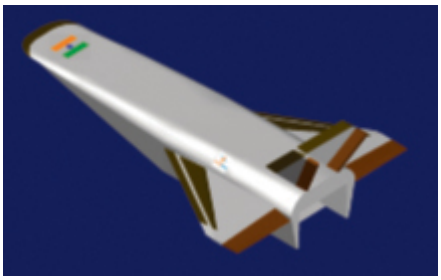


Simulator Internal

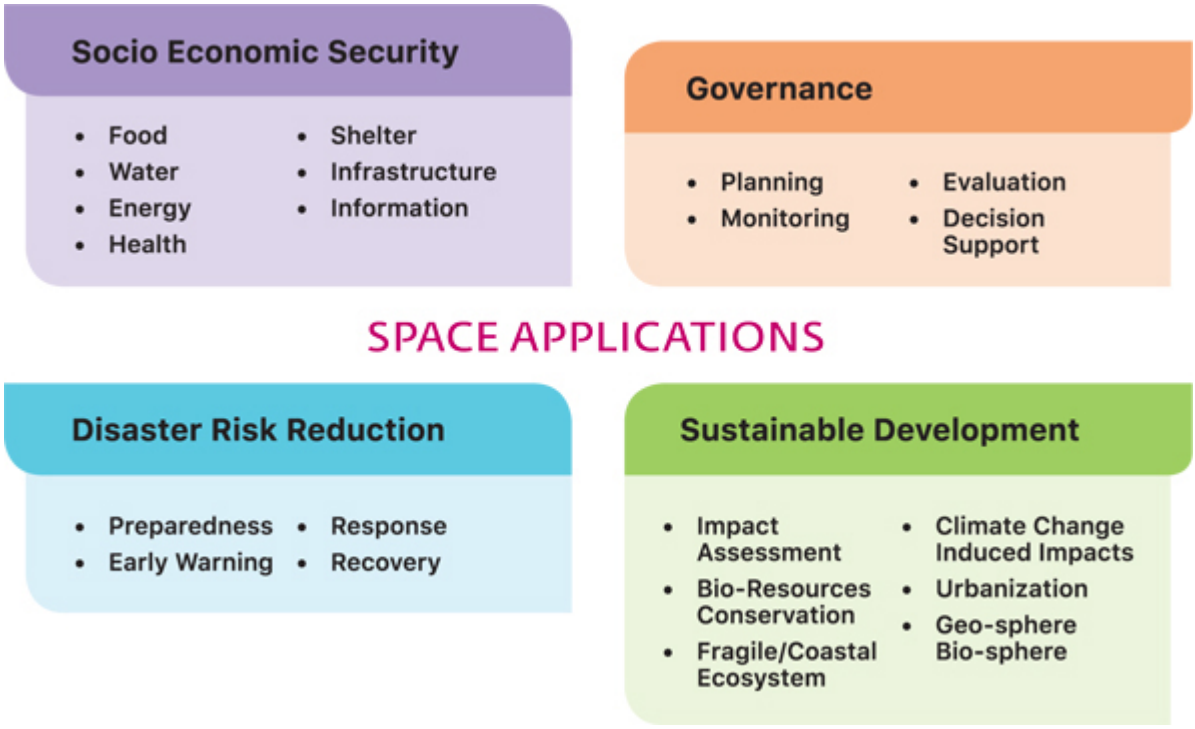
Space suit for Gaganyaan.

Pad abort test. An emergency provision for Gaganyaan.

High-thrust stationary plasma thrusters based on Xenon will enable the creation of indigenous all-electric communication satellites, replacing the heavier chemical propulsion systems. This would allow the accommodation of more payload within the same mass.



India joins leading space agencies working on space vehicles with air-breathing propulsion through a development programme focussing on the critical technologies leading to a technology demonstrator version of a Winged Hypersonic Vehicle with Airframe Integrated Systems and Supersonic Combustion Ramjet (SCRAMJET) propulsion.



List of Abbreviations

ADRIN: Advanced Data Processing Research Institute

Antrix: Antrix Corporation Limited

APPLE: Ariane Passenger Payload Experiment

ASLV: Augmented Satellite Launch Vehicle

CE: Cryogenic Engine

CES: Crew Escape System

CNES: Centre National d'Etudes Spatiales

CS: Cryogenic Stage

CSIR: Council of Scientific & Industrial Research

CUS: Cryogenic Upper Stage

DAE: Department of Atomic Energy

DECU: Development and Educational Communication Unit

DOS: Department of Space

DTH: Direct-to-Home

ESA: European Space Agency

ESCES: Experimental Satellite Communication Earth Station

GAGAN: GPS-aided GEO Augmented Navigation

GK: Glavkosmos

GLONASS: Global Navigation Satellite System

GPS: Global Positioning System

GSLV Mk III: Geosynchronous Satellite Launch Vehicle Mark III

GSLV: Geosynchronous Satellite Launch Vehicle

HSFC: Humans Space Flight Centre

IIRS: Indian Institute of Remote Sensing

IIST: Indian Institute of Space Science and Technology

IISU: ISRO Inertial Systems Unit

INCOSPAR: Indian National Committee for Space Research

INSAT: Indian National Satellite System

IPRC: ISRO Propulsion Complex

IRS-1A: Indian Remote Sensing Satellite-1A

ISAC: ISRO Satellite Centre

ISRO: Indian Space Research Organisation

ISTRAC: ISRO Telemetry, Tracking and Command Network

LEOS: Laboratory for Electro-Optics Systems

LPSC: Liquid Propulsion Systems Centre

MCF: Master Control Facility

MST: Mobile Service Tower

MTCR: Missile Technology Control Regime

NARL: National Atmospheric Research Laboratory

NASA: National Aeronautics and Space Administration

NE-SAC: North Eastern-Space Applications Centre

NRSC: National Remote Sensing Centre

PRL: Physical Research Laboratory

PSLV: Polar Satellite Launch Vehicle

RFF: Rocket Fabrication Facility

RPP: Rocket Propellant Plant

SAC: Space Applications Centre

SCL: Semi-Conductor Laboratory

SDSC: Satish Dhawan Space Centre

SHAR: Sriharikota Range

SITE: Satellite Instructional Television Experiment

SLV-3: India's first launch vehicle

SPL: Space Physics Laboratory

SRE: Satellite Capsule Recovery Experiment

SSTC: Space Science and technology Centre

TERLS: Thumba Equatorial Rocket Launching Station

URSC: UR Rao Satellite Centre

USSR: Union of Soviet Socialist Republics

VAB: Vehicle Assembly Building

VSAT: Very Small Aperture terminal

VSSC: Vikram Sarabhai Space Centre

ISRO's Yuva Vigyani Karyakram (Yuvika) is a two-week residential outreach programme in which over 110 children from schools in different States participated. This was conducted at four of the ISRO Centres: VSSC (Thiruvananthapuram), SAC (Ahmedabad), URSC (Bengaluru) and NE-SAC (Shillong). During this period, the children could listen to some veterans of ISRO, interact with the scientists and do some projects on their own. All the children gathered at SDSC-SHAR (Sriharikota) to spend a day with K Sivan, Chairman of ISRO. Picture shows children with K Sivan, S Pandian, TK Alex and PV Venkitakrishnan.

कार्यक्रम (युविका)
Programme (YuViKa)